Physics at the Energy Frontier

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1 Dec 97 at Brown University

I. Introduction: Fermilab, CDF, D0, etc.

II. The top quark

III. The *W* (and Higgs?) mass

IV. Supersymmetry: one candidate event?

talk is on http://www-d0.fnal.gov/~strovink/

The Standard Model

is a non-abelian gauge theory with symmetry groups

SU(3) (color) $\otimes$ SU(2) (hypercharge) $\otimes$ U(1) (charge)
----strong---- ---------------electroweak---------------

Strong interactions are described by Quantum Chromodynamics (QCD):

- color is the QCD analog of electric charge
- quarks come in doublets and in 3 colors
- force is mediated by 8 massless colored gluons

Electroweak interactions:

- quarks and leptons come in doublets
- force is mediated by 4 massless bosons
- symmetry breaking is responsible for the physical bosons (γ, Z^0, $W^{\pm}$, and the undiscovered Higgs)

Shortcomings of the standard model:

- many arbitrary masses, mixing angles
- origin of *CP* noninvariance?
- origin of fermion masses?
- strong-electroweak unification? gravity?

Matter constituents and force carriers

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2,...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$< 7 \times 10^{-9}$	0
e electron	0.000511	−1
ν_μ muon neutrino	< 0.0003	0
μ muon	0.106	−1
ν_τ tau neutrino	< 0.03	0
τ tau	1.7771	−1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.005	2/3
d down	0.01	−1/3
c charm	1.5	2/3
s strange	0.2	−1/3
t top (initial evidence)	170	2/3
b bottom	4.7	−1/3

BOSONS

force carriers
spin = 0, 1, 2,...

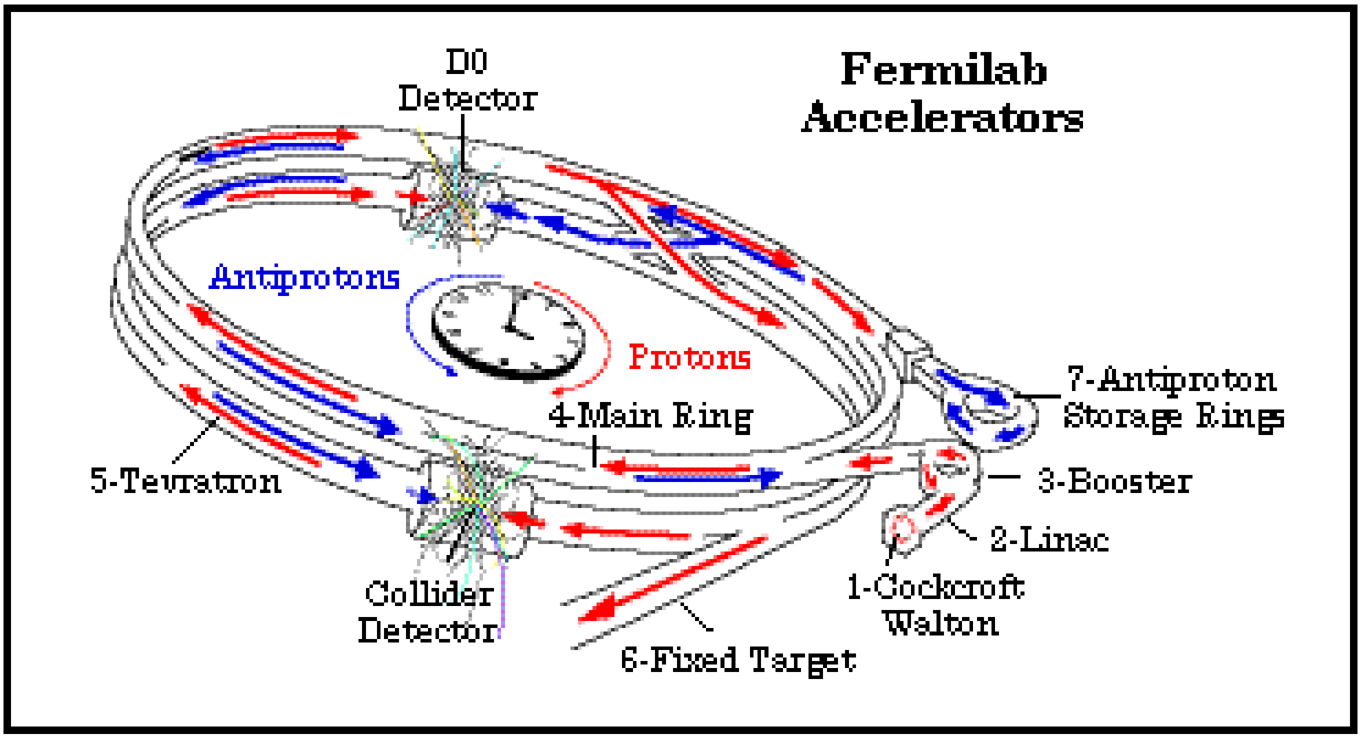
Unified Electroweak spin = 1	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.22	−1
W^+	80.22	+1
Z^0	91.187	0

Strong or color spin = 1	Mass GeV/c^2	Electric charge
g gluon	0	0

(1994 summary from the Contemporary Physics Education Project at LBNL)

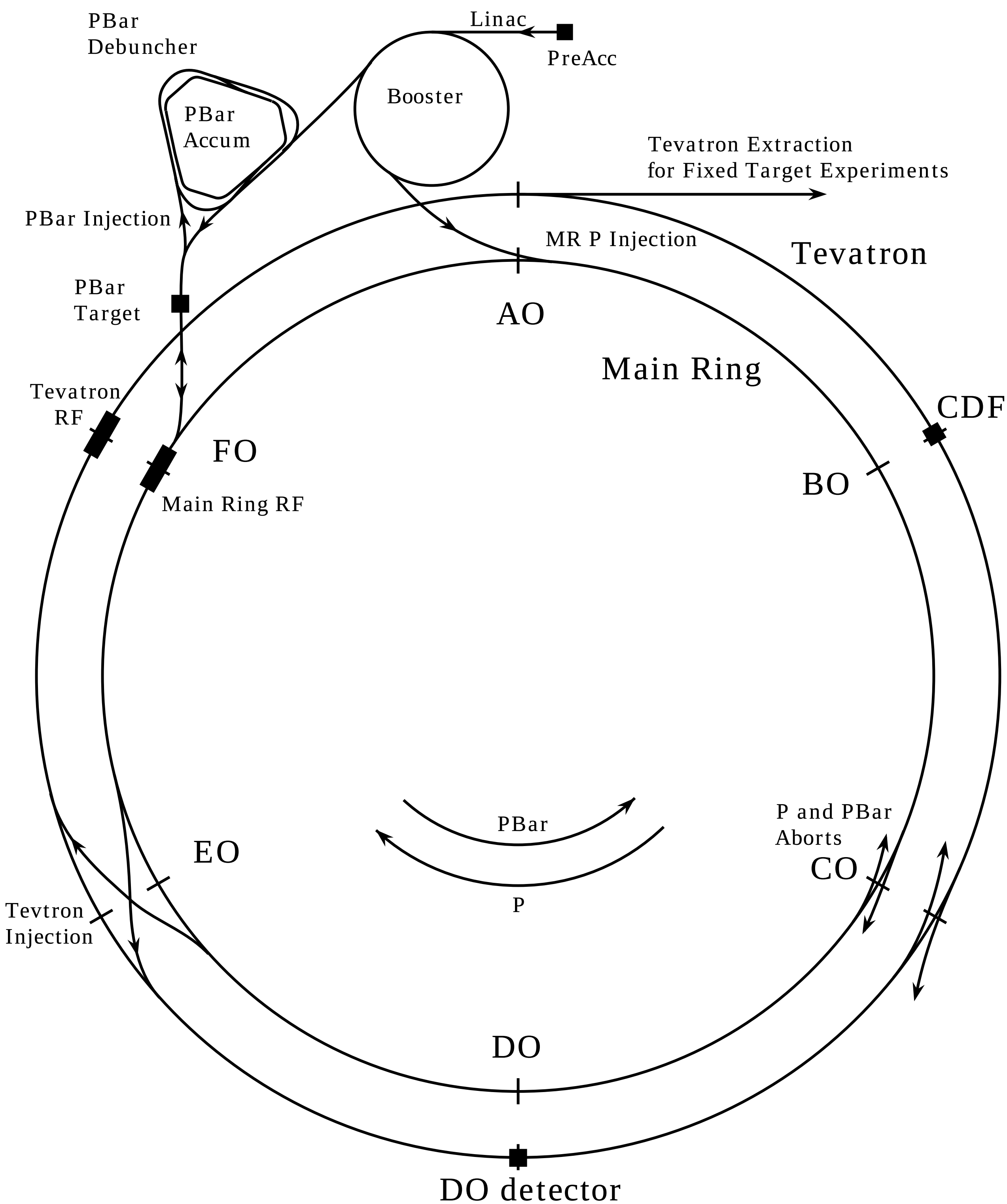
Fermilab Tevatron (Web view)

To produce and detect top via proton-antiproton collisions at Fermilab, 7 accelerators and 2 detectors were used:

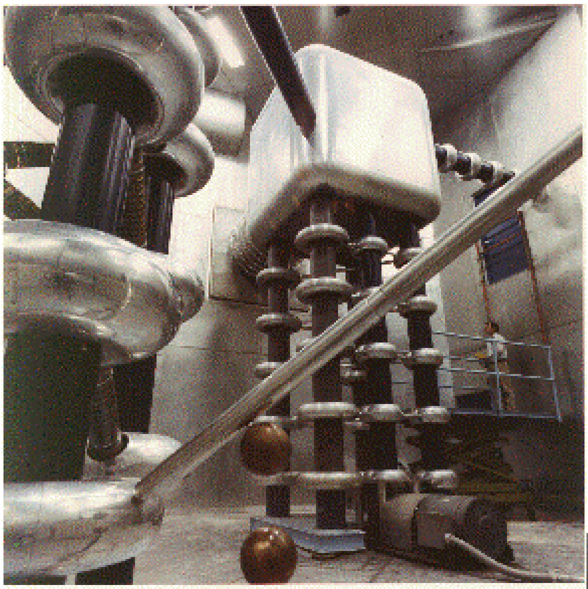


Fermilab Tevatron (plan view)

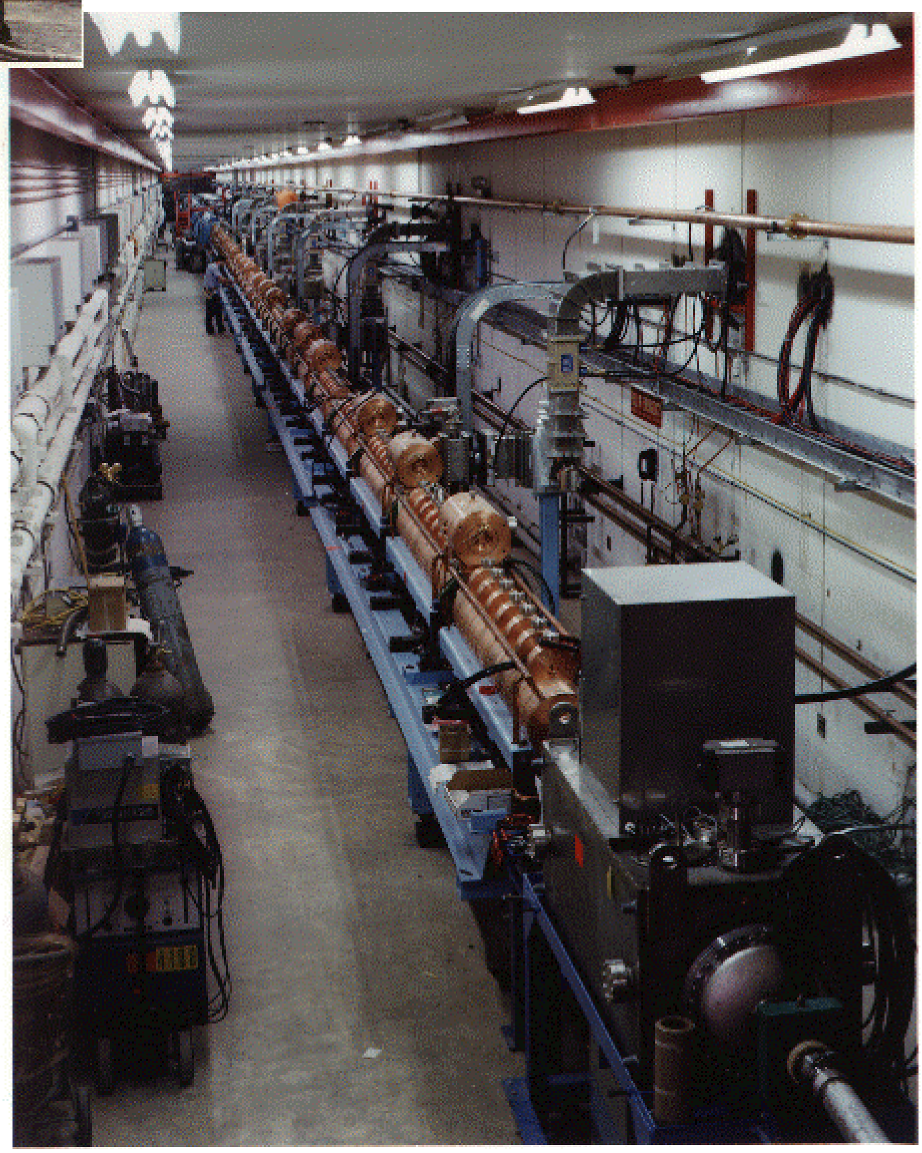
Here are the 7 accelerators again, more closely to scale:



Birth and death of an antiproton: gestation

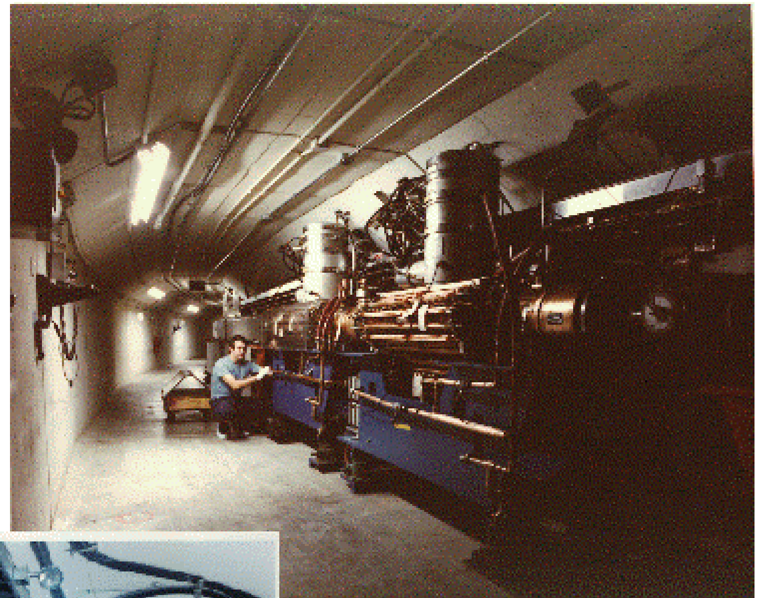


Cockroft-Walton (H^- ions)
1 MeV

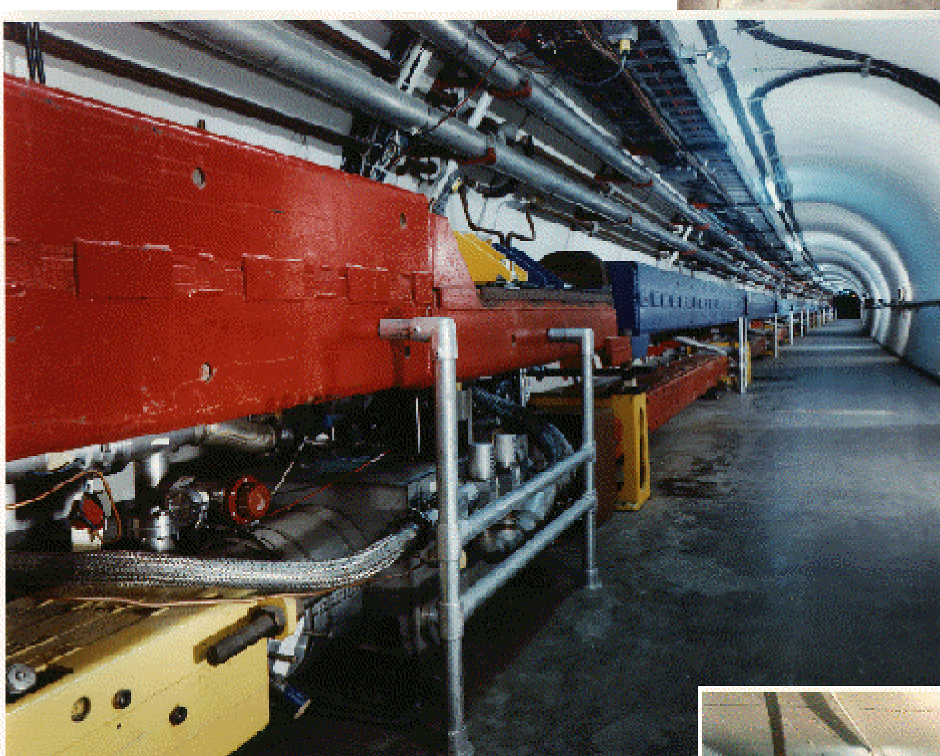


Linac (H^- ions)
400 MeV

Birth... (cont'd)



Booster (H^- ions)
8 GeV

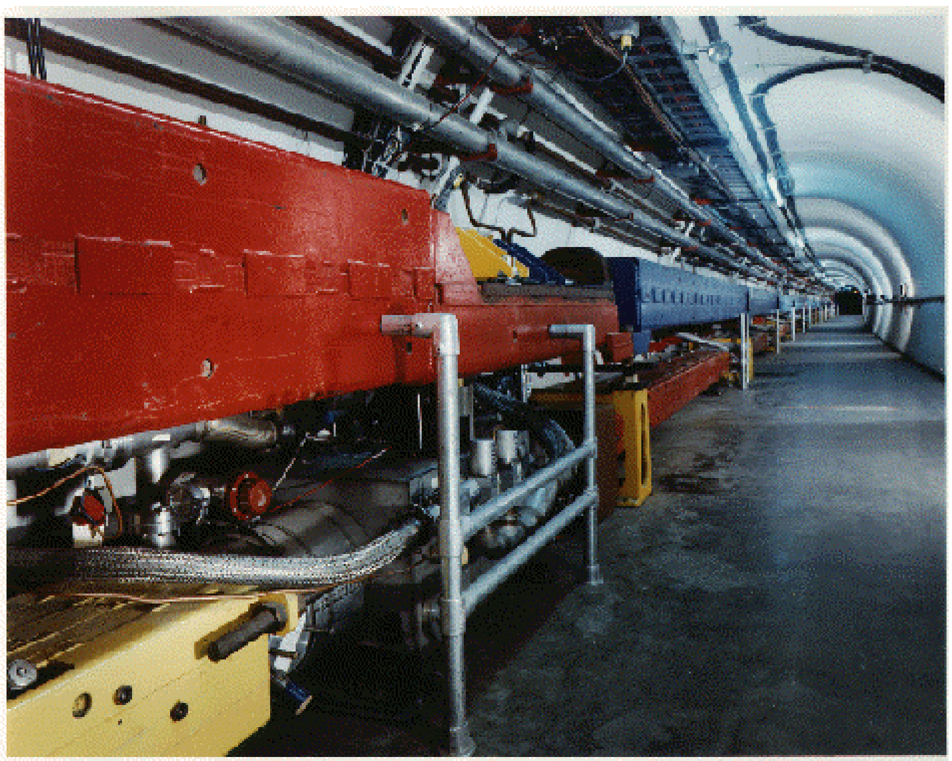


Main Ring (*p*'s)
120 GeV
(being replaced
by Main Injector)

Debuncher and
Accumulator (anti-*p*'s)
8 GeV

Birth and death of an antiproton (cont'd)

Finally, the accumulated stack of 8 GeV antiprotons, plus a new batch of 8 GeV protons from the Booster, are accelerated to 900 GeV by the Main Ring and the superconducting Tevatron working in tandem.



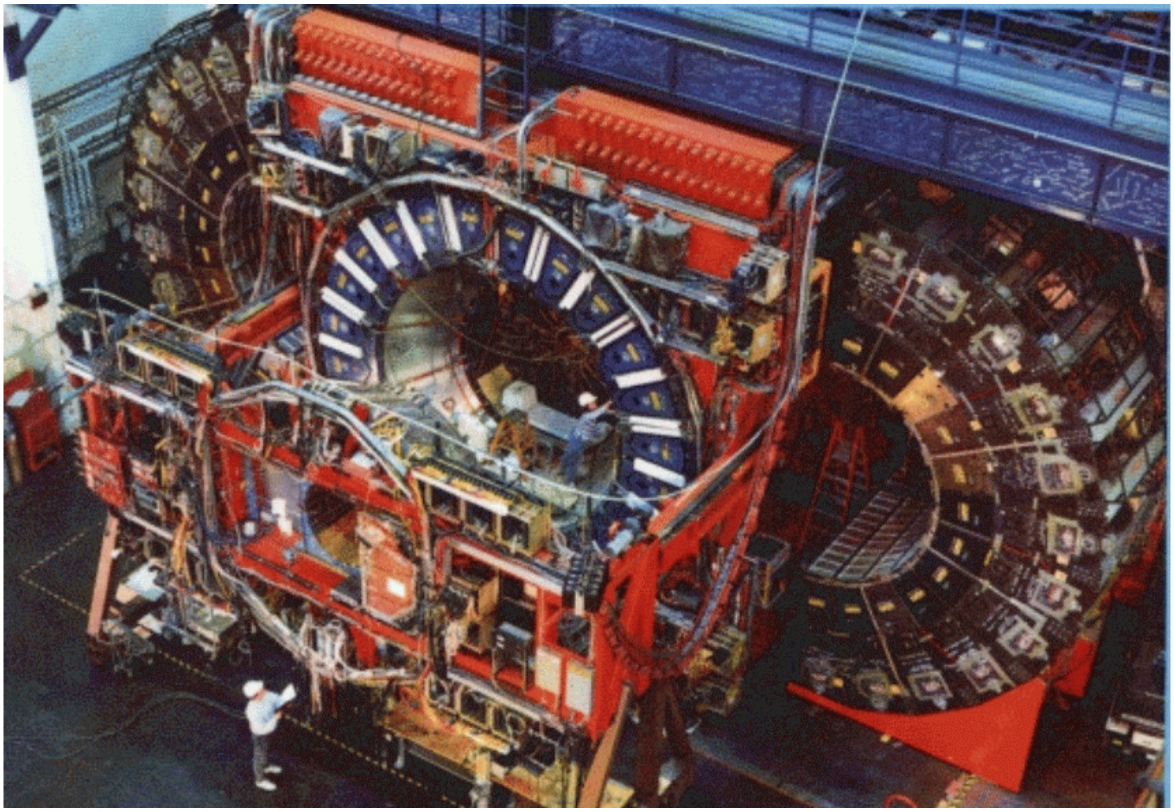
Main Ring
(*p*'s and anti-*p*'s)
150 GeV

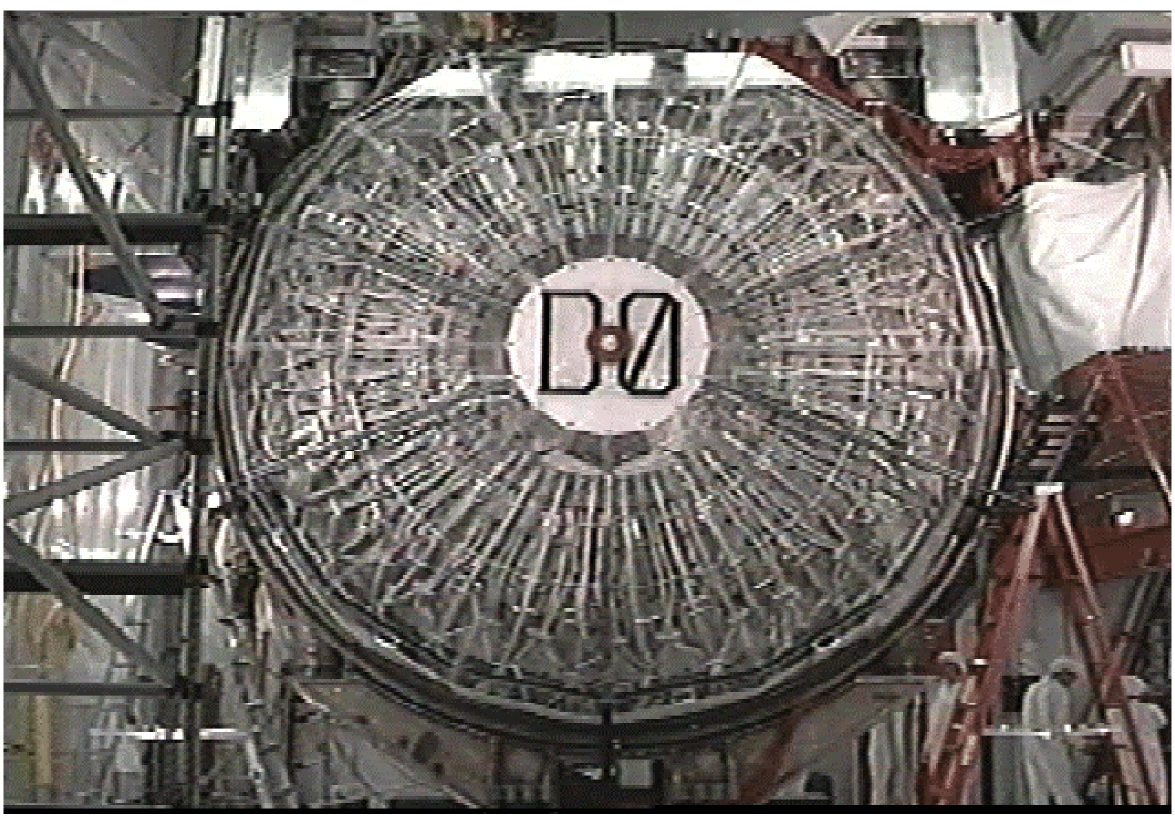
Tevatron
(*p*'s and anti-*p*'s)
900 GeV

The two counter-rotating beams are focused and brought into collision at the CDF and D0 detectors.

Birth and death of an antiproton: annihilation

CDF





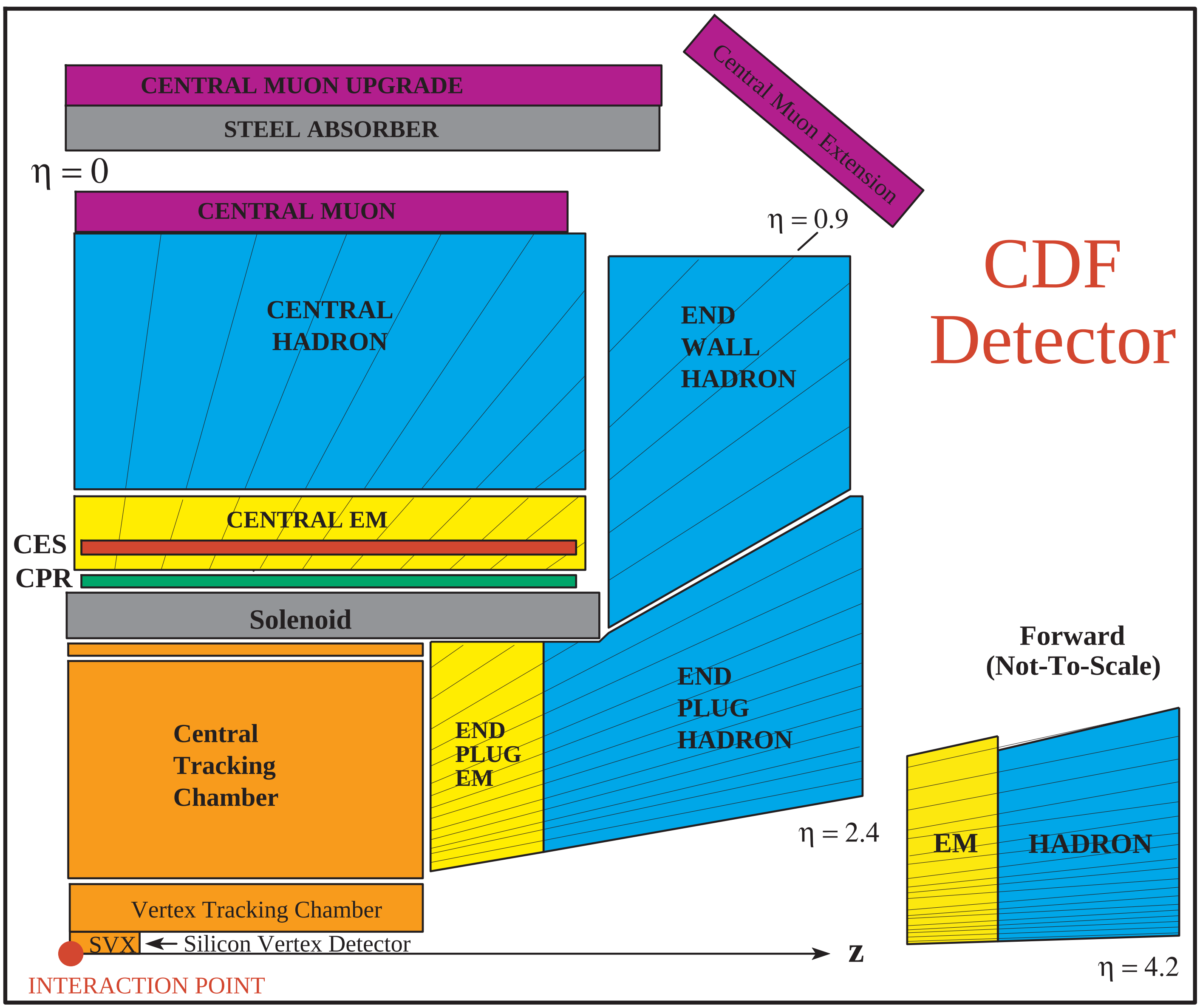
D0

CDF detector: quarter section view

CDF emphasizes measurement of individual charged particles within a 1.5 T solenoidal magnetic field, including detection of vertices displaced from the interaction point *e.g*. because of the *b* quark lifetime.

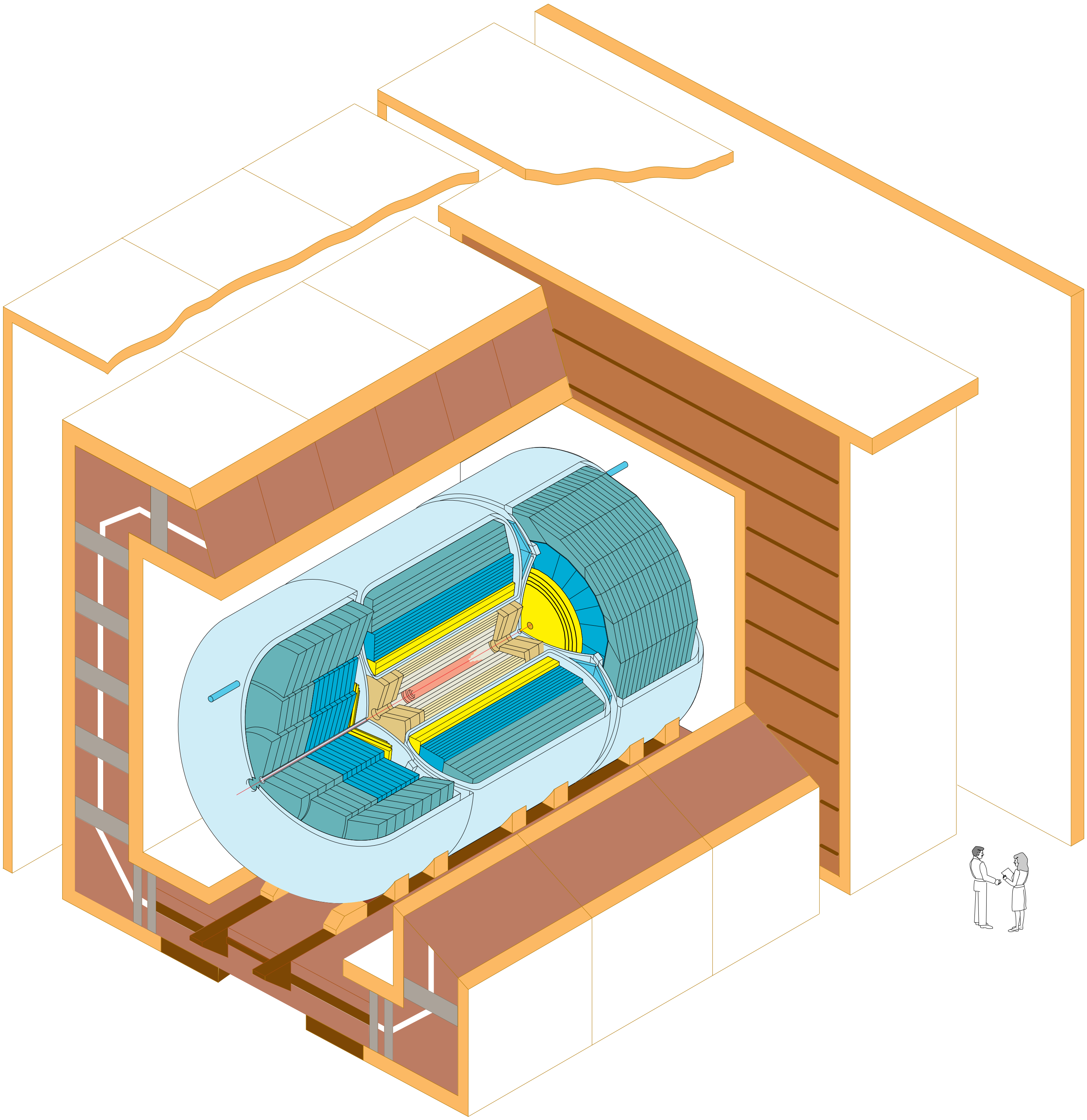
Central electron detection is good. Central muon acceptance extends to low p_T with fair background rejection.

Calorimetric detection of jets and missing E_T is adequate after corrections for nonuniformities are performed.



D0 detector: isometric view

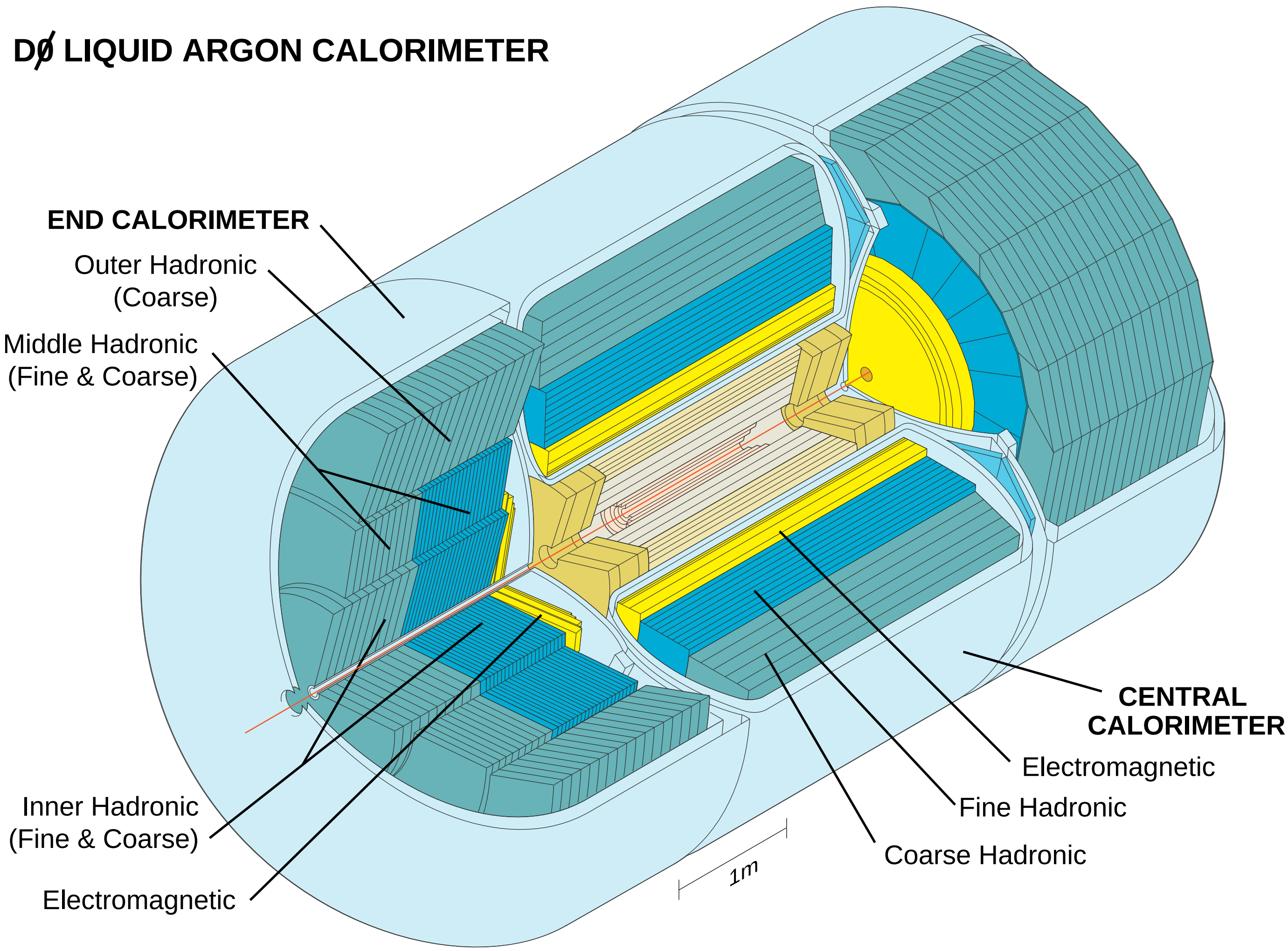
D0 is a nonmagnetic detector, except for iron toroids providing coarse muon p_T resolution with low background.



DØ Detector

D0 calorimeter: isometric view

D0 emphasizes calorimetric detection of jets and missing E_T. Its liquid argon / U sampling calorimeter is especially uniform, hermetic, and fine-grained.

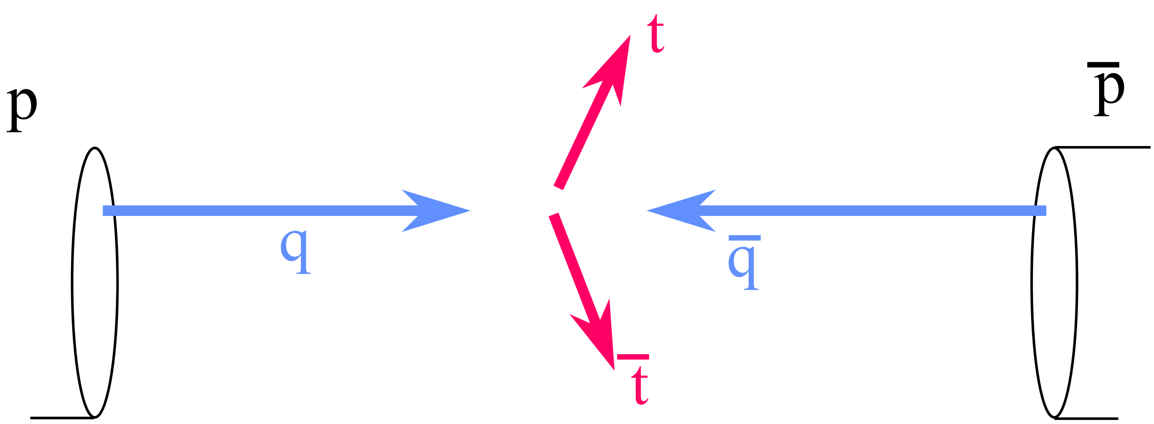


Inside the calorimeter was a modest tracking system used mainly to aid in identifying electrons and muons.

For the run beginning in ~1999, a 2T solenoid and a scintillating fiber/silicon tracker are being added.

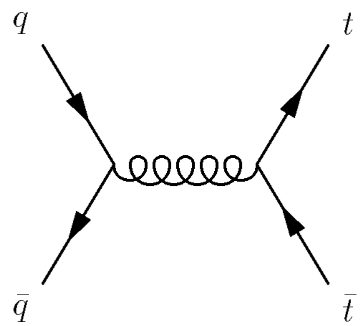
Both CDF and D0 are being upgraded as well to handle an order of magnitude increase in event rate.

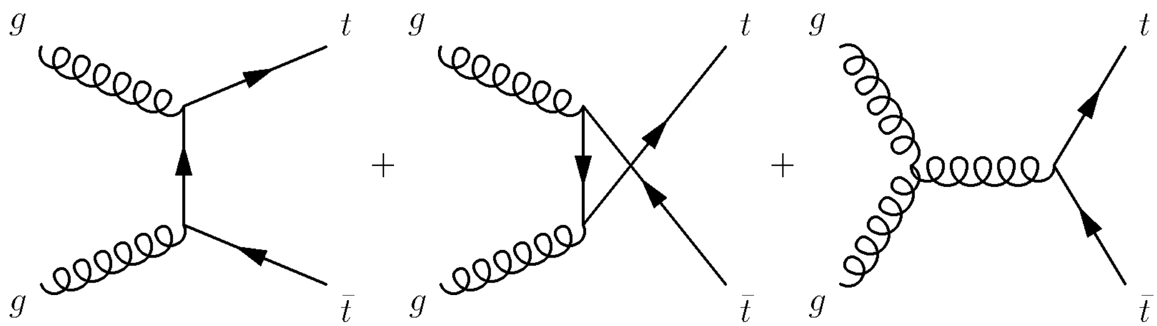
Top pair production is a rare process



Process	σ (pb)
2 jets	3.1×10^6
4 jets	125,000
6 jets	5,000
W	25,000
Z	11,000
WW	10
tt	5

How top production occurs:





Top pairs are produced in the *s*-channel by quark-antiquark or gluon-gluon fusion. To leading order (diagrammed above) at the Tevatron, the quark-antiquark channel dominates by ~1 order of magnitude.

Higher-order processes are especially important for the gluon-gluon process because of initial-state emission of soft gluons. It is necessary to resum to all orders the dominant contributions from these diagrams. Variations in the resummation procedure as well as the usual QCD renormalization scale cause ~ ±20% uncertainties in the calculated cross section.

Single top is produced in the *t*-channel at similar rates. The backgrounds are much higher than for top pairs, so single top plays little role in present analysis.

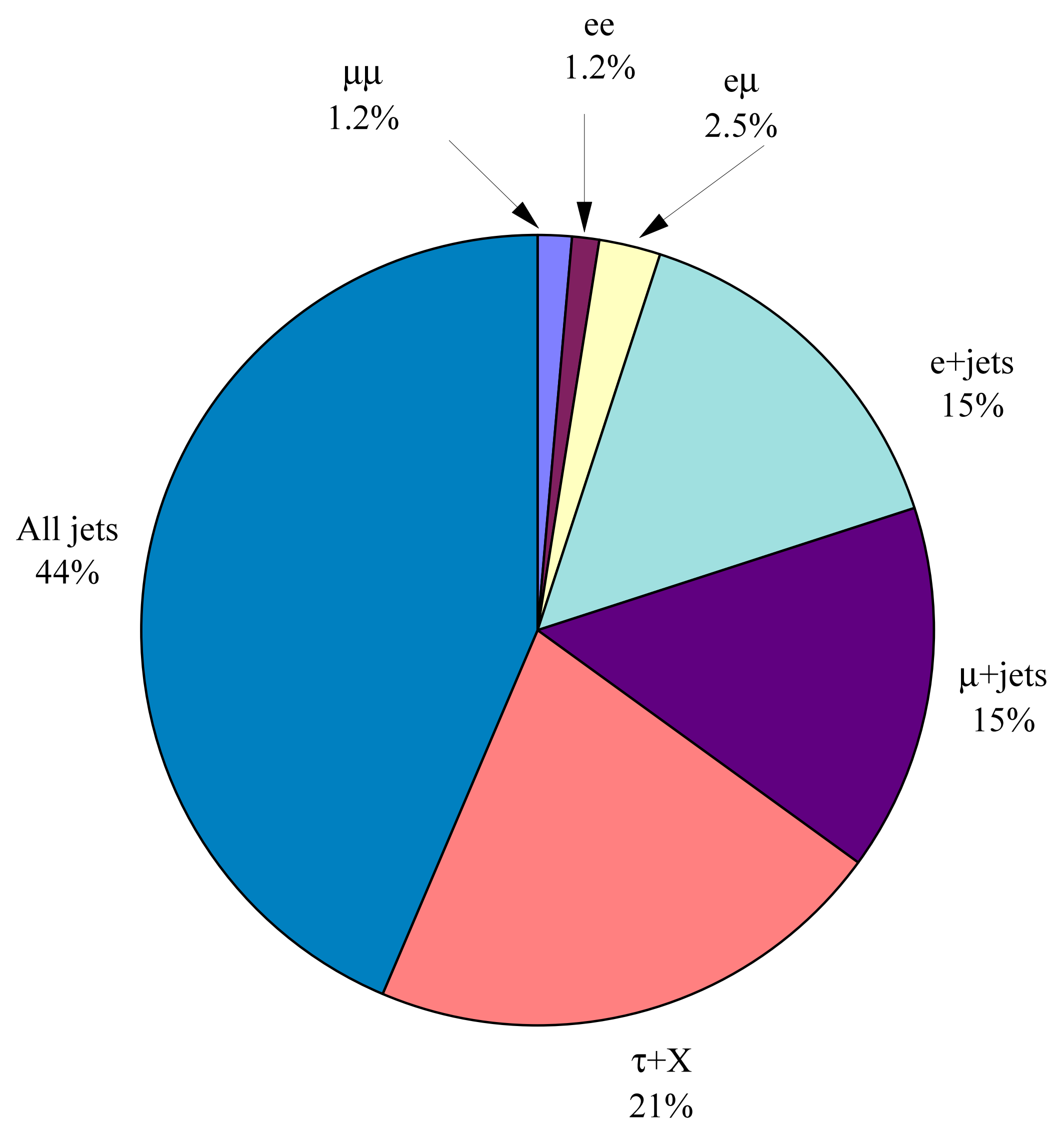
Classification of top pair events by *W* decay channel

Assume that all top quarks decay via W+b.

W branching ratio is 1/9 per lepton and 3/9 per (colored) quark generation, leading to the chart below.

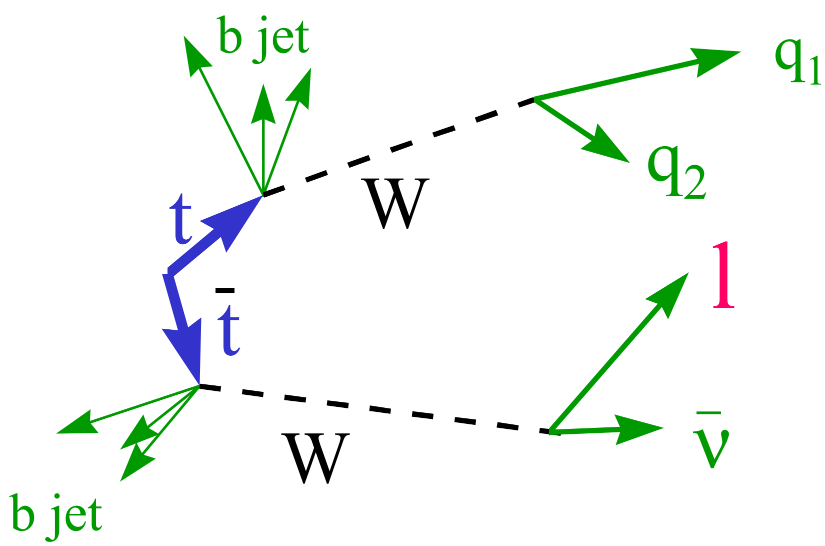
Most information on top cross section and mass comes from "lepton+jets" and "dilepton" channels, where "lepton" refers to electron and/or muon.

A ~3σ top signal is also observed in the "all jets" channel by both experiments.

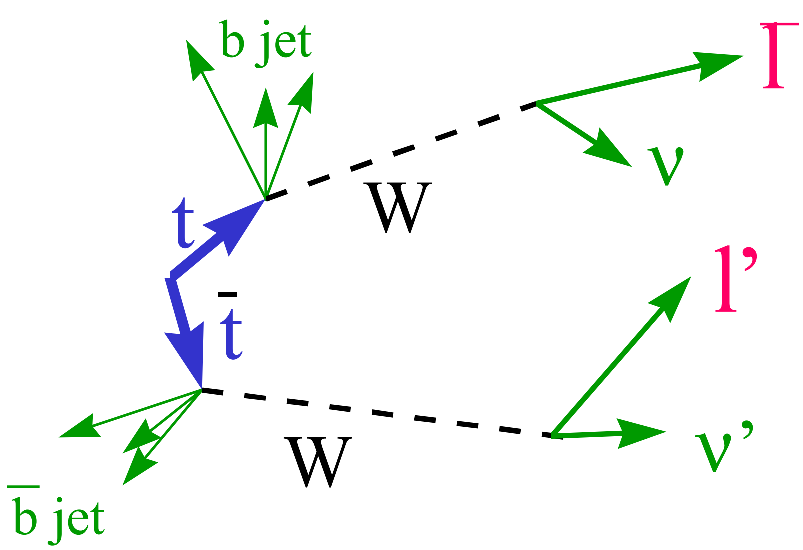


Lepton+jets and dilepton channels

We are concerned mainly with decay of top pairs into one isolated electron or muon plus 4 jets.



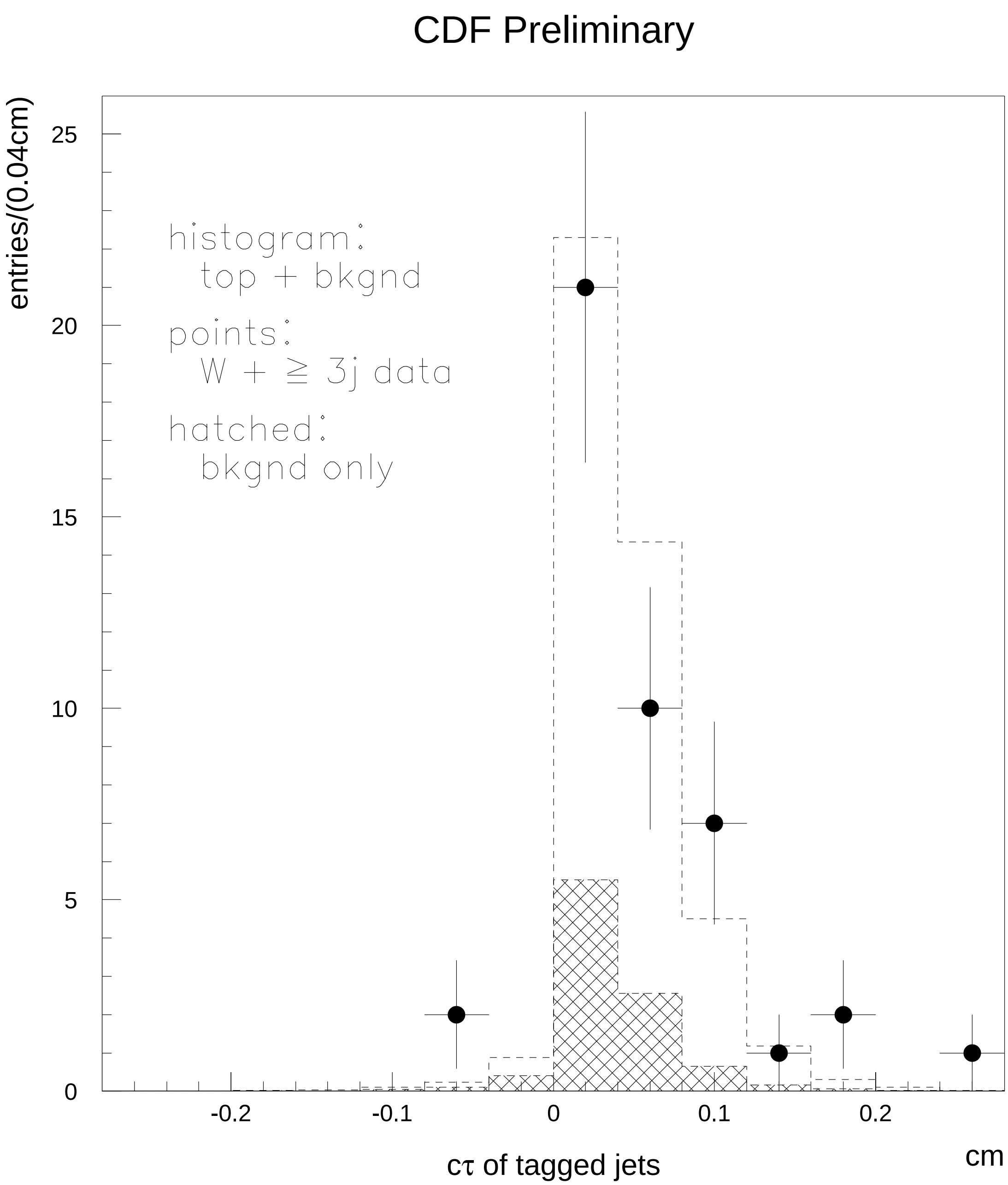
Top pair decay into two isolated leptons (*e* or μ) plus 2 jets is also an important channel.



Displaced vertex from *b* decay in lepton+jets channel

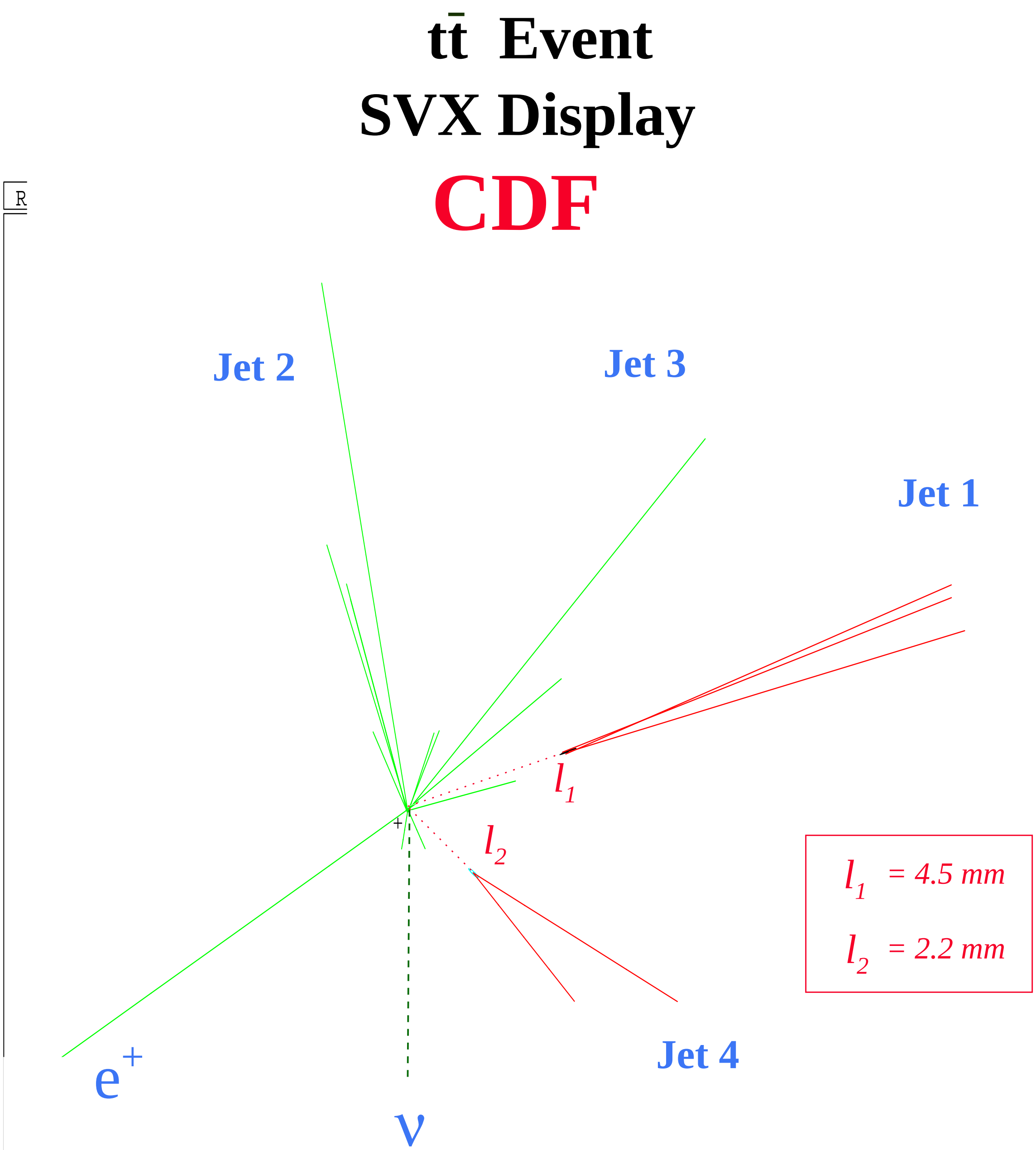
A *b* hadron with p_T=10 GeV/*c* decays at $<\sqrt{x^2+y^2}>$ ~1 mm from the beam axis. A CDF SVX tag requires a 2 (>2) track vertex with a >3σ (>2σ) *xy* impact parameter.

Displayed is the *c*τ distribution of tagged jets. The data and top are slightly broader than the background.



First CDF top event

CDF's first top candidate with low background probability had two separated vertices (from *b* decay) and two pairs of jets which reconstruct to a mass near that of the *W*.



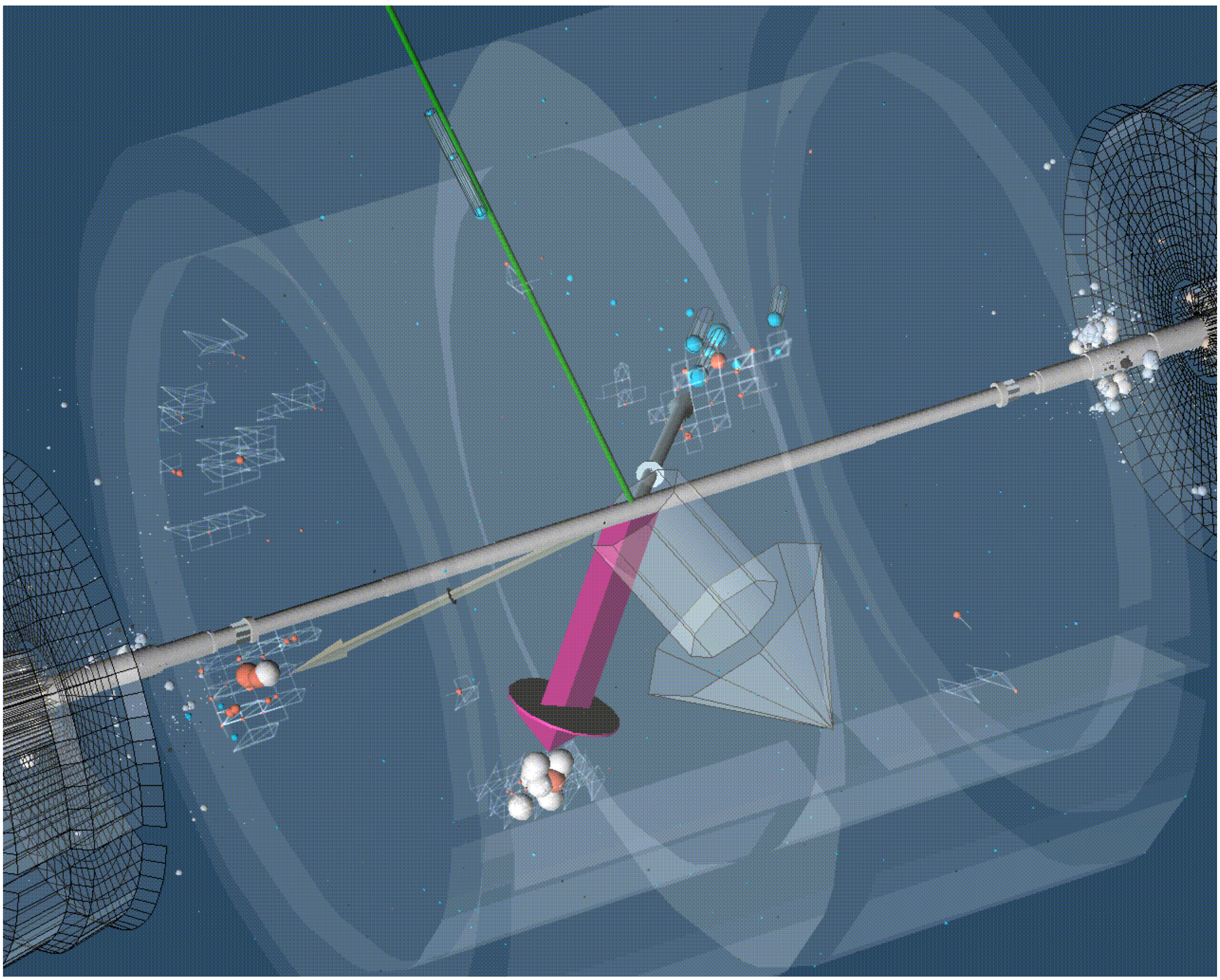
$M_{top}^{Fit} = 170 \pm 10$ GeV/c^2

24 September, 1992
run #40758, event #44414

First D0 top event

The first D0 top candidate with low background probability was an $e + \mu + 2$ jet event with extraordinarily high electron (magenta) E_T , muon (green) p_T , and missing E_T (thick arrow).

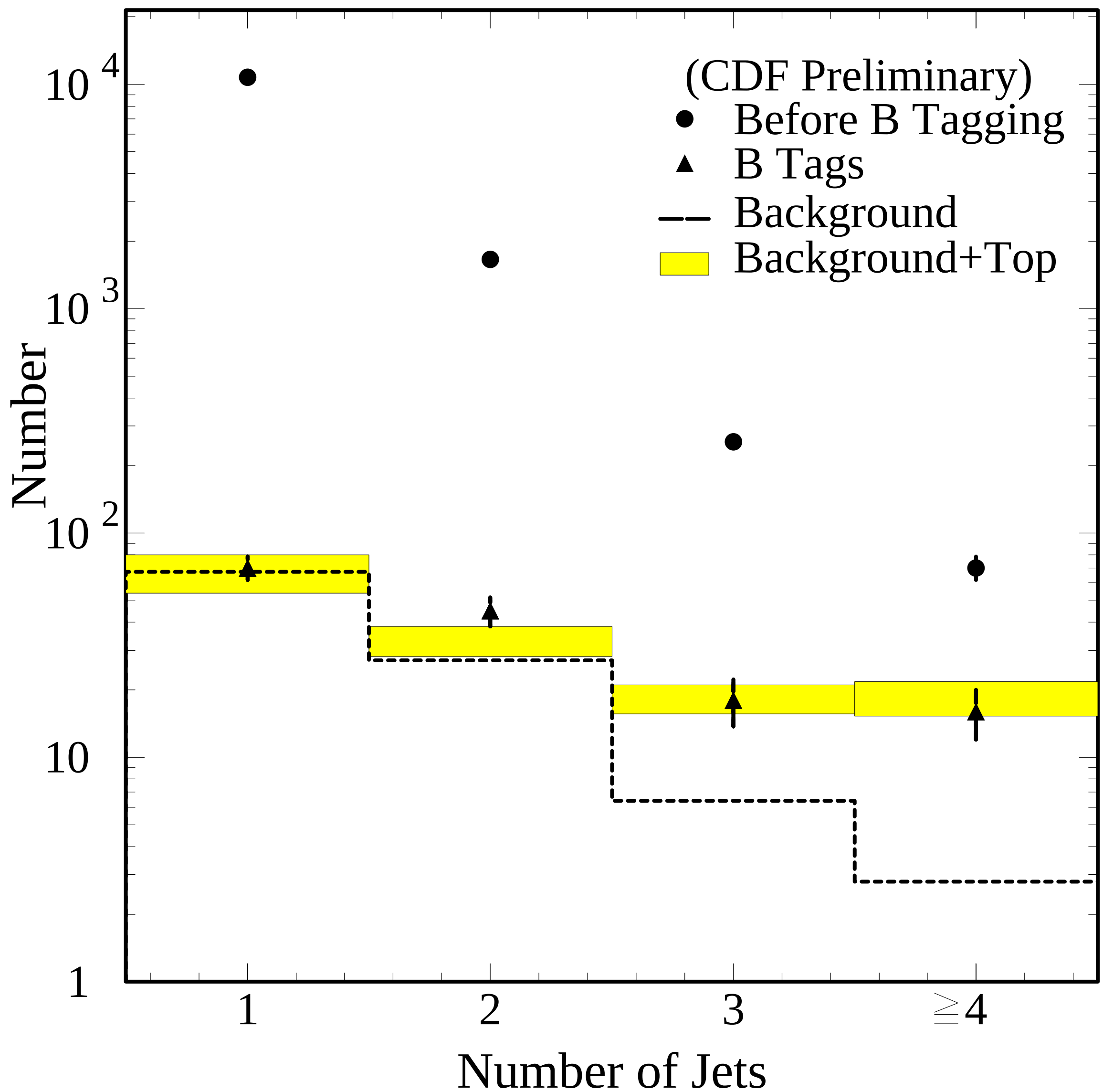
The grey arrows are the two jets; the spheres are energy deposits in the calorimeter cells.



Jet multiplicity in lepton+jets channel enhanced by displaced vertex tag from *b* decay

After all cuts including the SVX tag are imposed, CDF sees a clear excess over background for ≥3 jets. This excess constrains the size of the top signal plotted.

In the 2 jet channel, 45 SVX tags are seen (6 double tagged), while 29 background + 6 top = 35 are expected. The 2 jet excess is not significant.

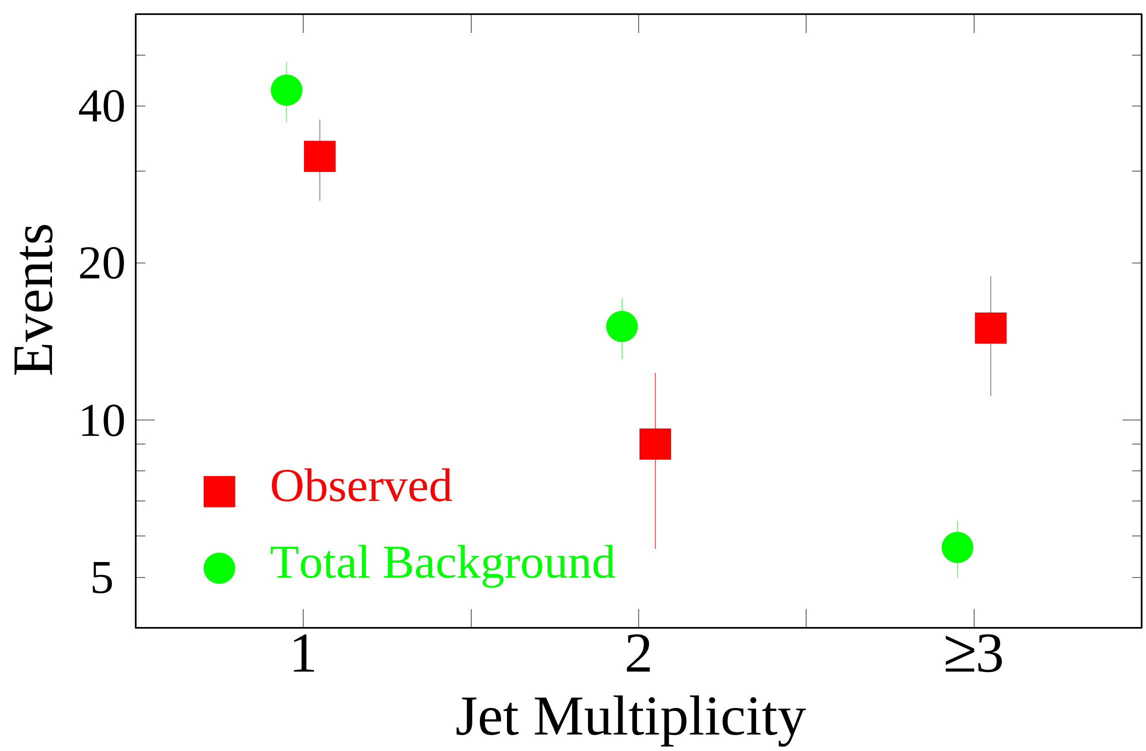


Jet multiplicity in lepton+jets channel enhanced by muon tag from *b* decay

~40% of top pairs yield an extra soft muon from the decay of one *b* or its daughter *c* quark, which is detected with ~50% efficiency.

The background to tag muons is particularly low in D0, with its short flight path and a thick muon filter. Only ~0.5% of generic QCD jets have a soft muon tag.

The D0 data show not only an excess over background in the signal region (at least 3 jets), but also consistency with expectation for lower jet multiplicities.

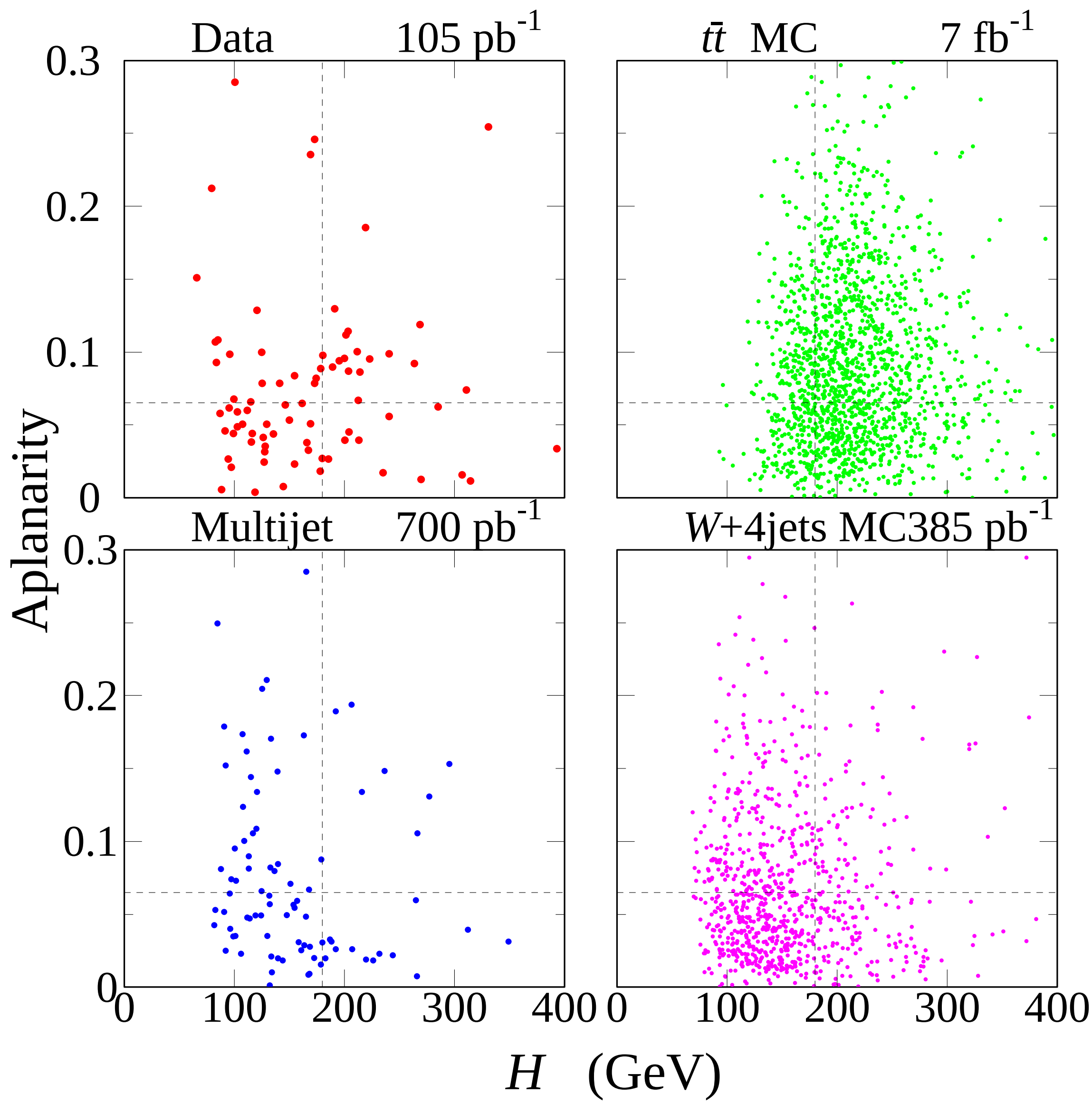


The background depends logarithmically on the number of jets. In the *l*+jets channel, where the lack of a μ tag allows larger backgrounds, this dependence is used to estimate the background level before stringent kinematic cuts are applied.

Lepton+jets channel enhanced by topological cuts

For the l+jets channel, without a μ tag, D0 makes a stringent final cut on aplanarity ($A > 0.065$) and on summed jet E_T ($H_T > 180$ GeV). (A is 3/2 the smallest eigenvalue of the normalized laboratory momentum tensor, including the jets and the W).

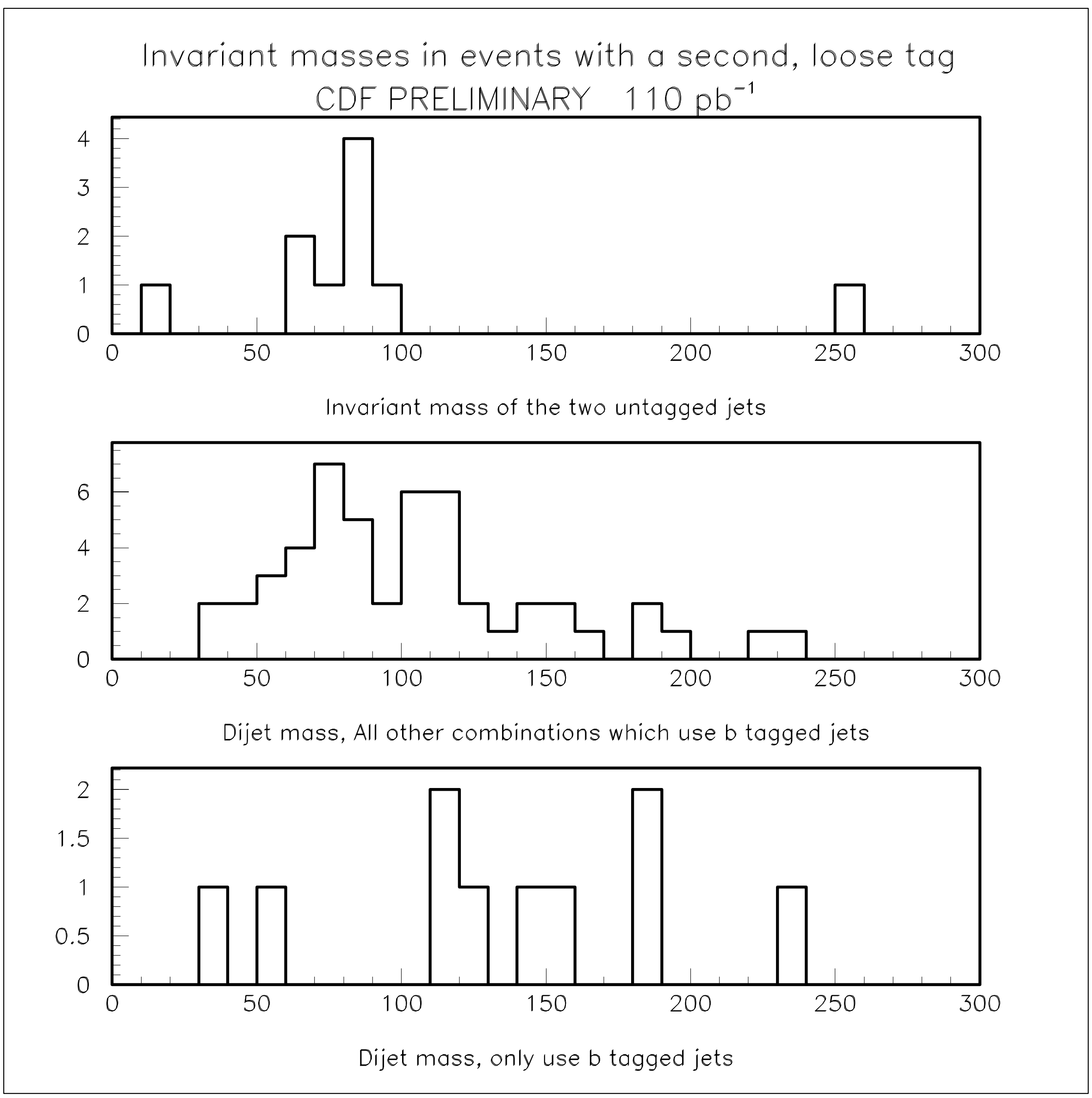
Shown is the distribution in A vs. H_T for data, top, W+jets background, and QCD multijet background. In each panel, only the events in the top right sector pass the cut.



CDF lepton + 4 jet sample with 2 *b* tags

In addition to the standard SVX and SLT tags, CDF also considers as loosely *b* tagged those jets which have less than 5% probability to be prompt according to SVX criteria. A subset of the lepton + 4 jet sample requires 2 *b* tags, one of which is usually loose.

Plotted for such events is the dijet invariant mass of pairs of jets which contain 0, 1, or 2 *b* tags. The untagged pairs cluster in the *W* mass region 60-100 GeV/c^2.

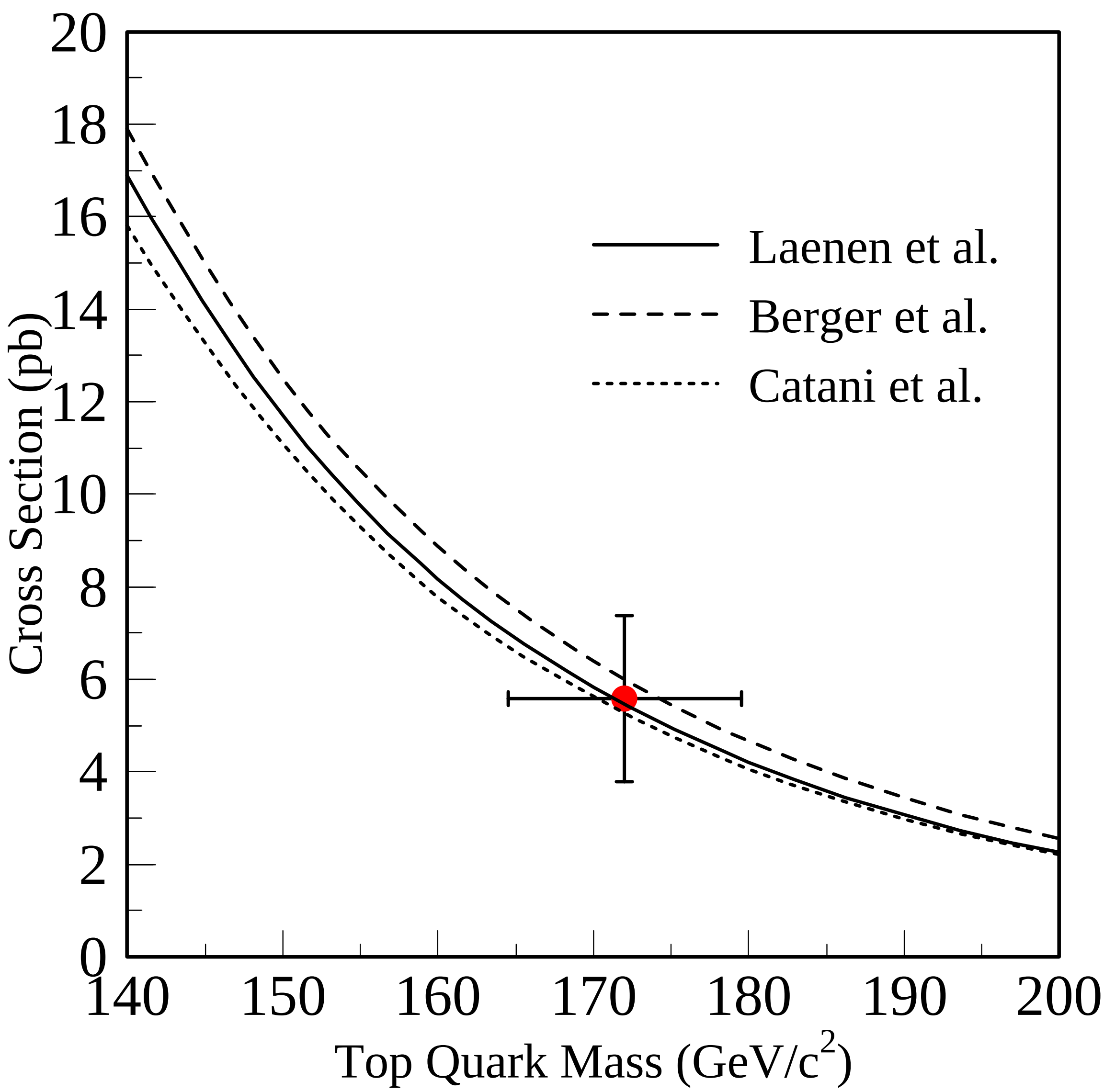


CDF & D0 top cross section measurements

The 1994 “*Evidence…*” (CDF) and 1995 “*Observation…*” (CDF and D0) papers reported larger than expected top cross sections. These excesses likely were fluctuations.

The D0 point is plotted below; the CDF point is added by hand.

Presently measured cross sections are in satisfactory agreement with all three NLO calculations.



Measuring the top mass in the lepton + 4 jet final state

In lepton + 4 jet events, all the final state variables are measured, except for $p_z(\nu)$. Adding the three constraints

$$
\begin{aligned}
m(W(\rightarrow l\nu)) &= m^W_{\rm pole} \\
m(W(\rightarrow q_{\rm jet3}\,\bar{q}_{\rm jet4})) &= m^W_{\rm pole} \\
m(b_{\rm jet1}W(\rightarrow l\nu)) &= m(b_{\rm jet2}W(\rightarrow q_{\rm jet3}\,\bar{q}_{\rm jet4}))
\end{aligned}
$$

allows a 2C kinematic fit.

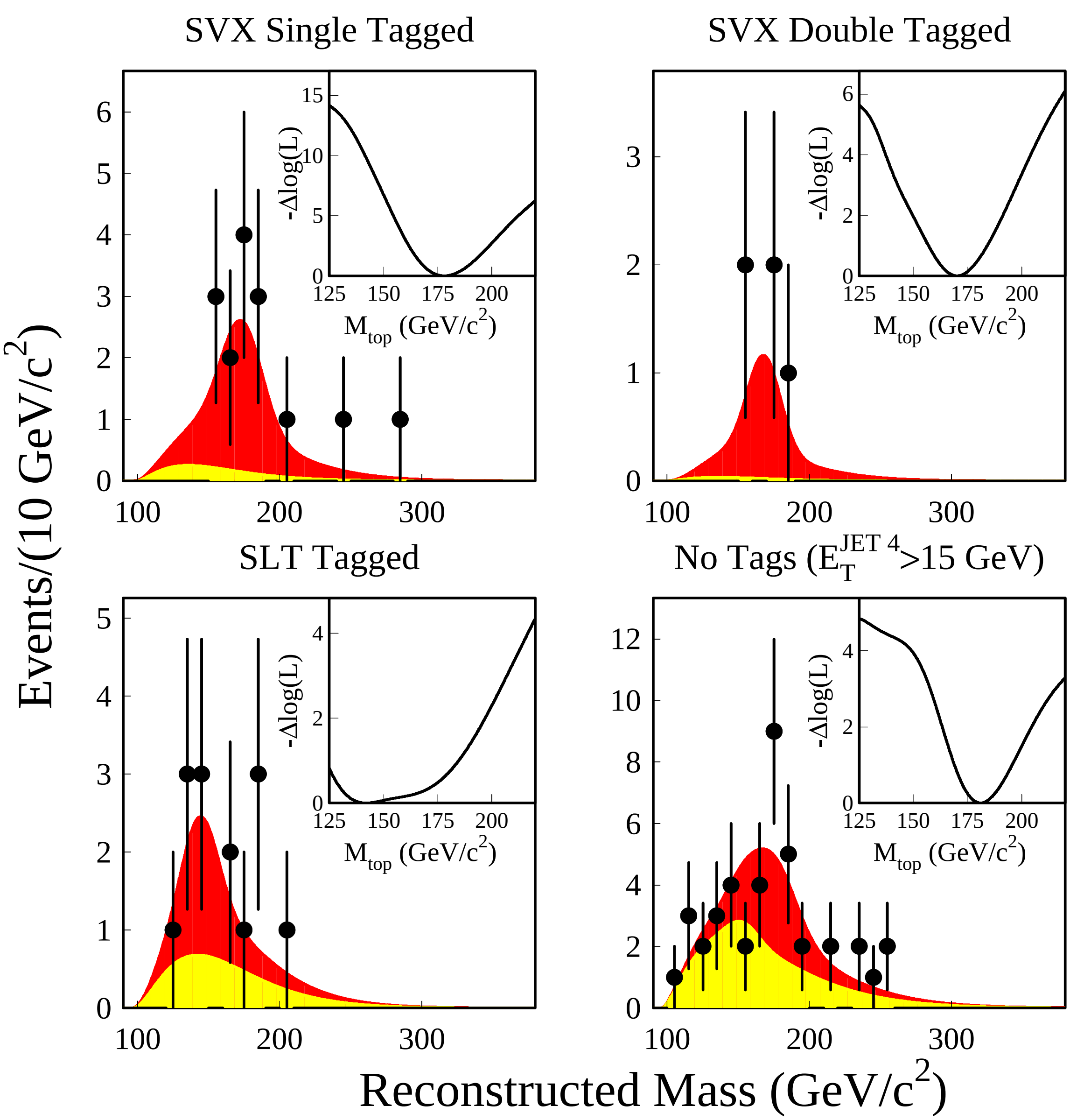
There are 12 possible jet assignments (6 for μ tagged events). Usually the fitted m_t varies strongly as $b_{\rm jet1}$ is reassigned(4 permutations), and less strongly as $b_{\rm jet2}$ is reassigned when $b_{\rm jet1}$ is fixed (3 permutations or 1). Also, for a fixed jet assignment, usually there are local χ^2 minima for each of 2 solutions for $p_z(\nu)$.

Minimizing χ^2 does yield the best fit to a fixed permutation, but for typical measuring errors the lowest χ^2 permutation is often not correct. Also, initial and final state gluon radiation frequently cause the four highest E_T jets not to correspond to the four quarks to which we wish to fit.

Thus the m_t linewidth is due mainly to combinatoric and QCD radiative effects.

Top quark mass determination by CDF

To measure the top mass in the lepton+jets channel, CDF analyzes separately the subchannels with (a) one or (b) two vertex *b* tags, (c) one soft lepton tag, and (d) no tag.



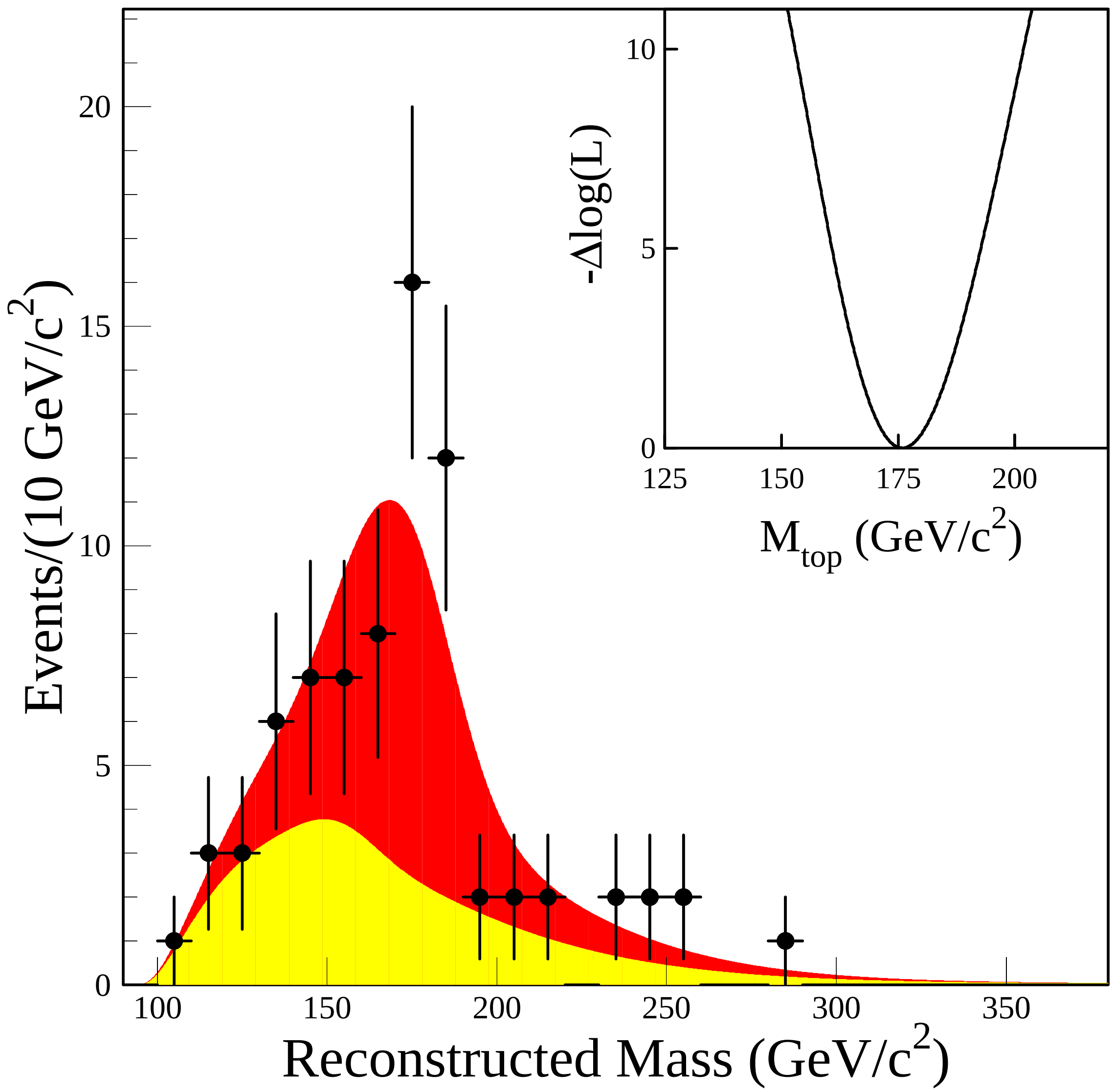
The largest contribution to the total information on the top mass is made by the single tagged channel.

Top quark mass determination by CDF (cont'd)

CDF's mass likelihood fit to 76 events (~31 bkgnd) takes into account the variations in S/N in the 4 channels:

$$\boldsymbol{m(t) = 175.9 \pm 4.8(\text{stat}) \pm 4.9(\text{syst})\ \text{GeV}/c^2}$$

For both experiments, the top mass systematic error is dominated by uncertainties in jet energy scale and initial and final state radiation.



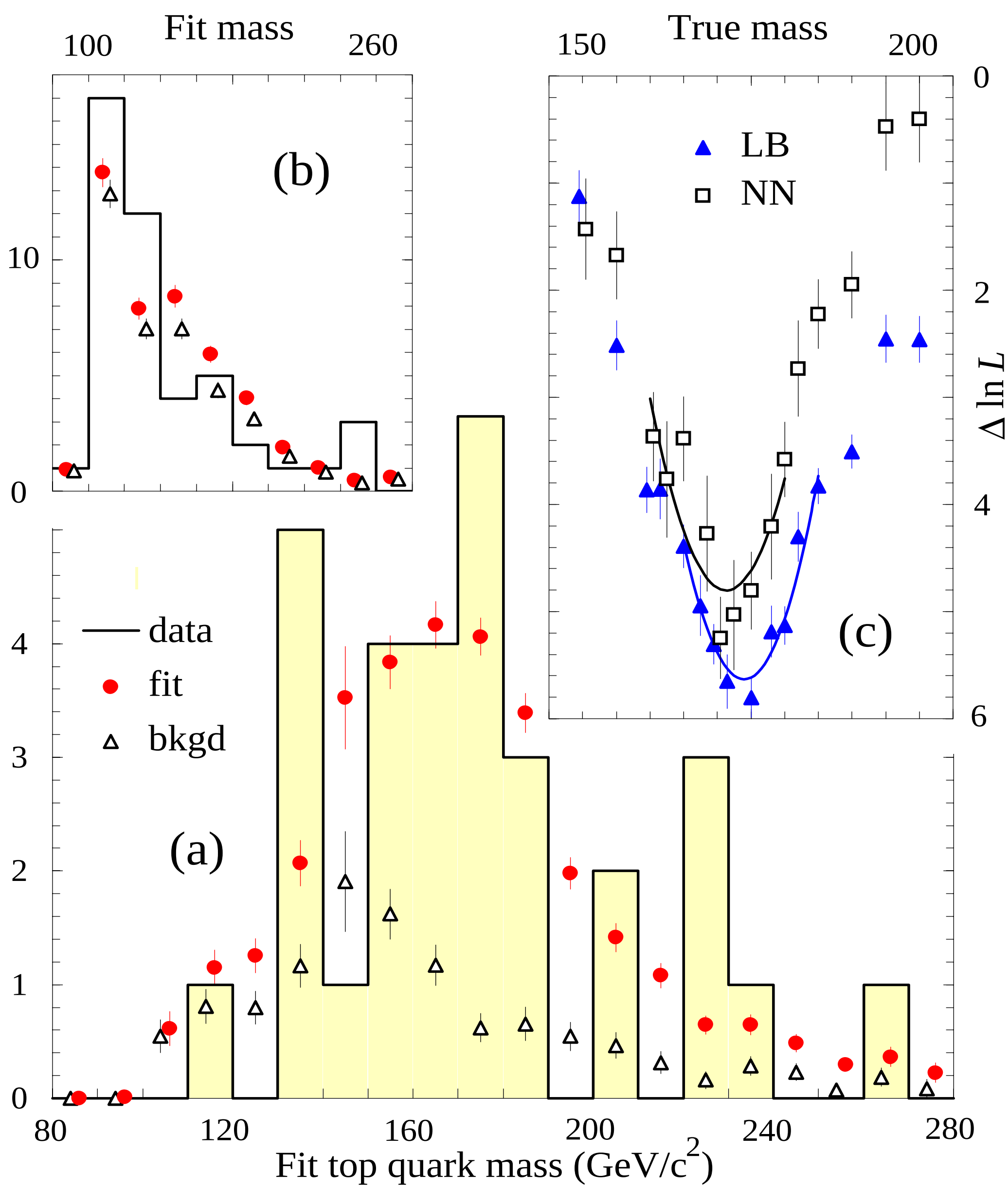
Top quark mass determination by D0

Data are plotted in (a) top-rich or (b) background-rich regions, based on a multivariate discriminant using kinematic variables that are only weakly correlated with m_{fit} .

For each true top mass plotted in (c), a likelihood fit to data is made for a free mixture of top signal and background, binned in top richness vs. m_{fit} . A parabolic fit yields

$$m(t) = 172.0 \pm 5.1(\mathrm{stat}) \pm 5.5(\mathrm{syst})\ \mathrm{GeV}/c^2$$

when mass information from dilepton events is included.



Motivation for measuring the W mass

In the Standard Model at tree level the W mass is determined by the precisely measured parameters

$$m_Z = 91.1865(20) \text{ GeV}$$
$$G_\mu = 1.16639(2)\times10^{-5} \text{ GeV}^{-2}$$
$$\alpha^* = 1/128.896(90) \,,$$

where G_μ is the Fermi coupling constant measured from the muon lifetime and corrected for purely electromagnetic loops, and α^* is the fine structure constant evaluated at $q^2 = m_Z^2$. The W mass is given by

$$m_W = m_Z \cos\theta_W = 79\,958 \text{ MeV}/c^2 \,,$$

where θ_W is the weak mixing angle defined by

$$\sin^2(2\theta_W) = (4\pi\alpha^*/\sqrt{2}) \,/\, G_\mu m_Z^2.$$

Beyond tree level, the W mass is shifted by the factor

$$(1\text{-}\Delta r)^{-1/2}$$

by a loop diagram involving the t and b quarks and another involving the Higgs boson. Δr is proportional to $(m_t/m_W)^2$ or $\ln(m_H/m_W)$ in the infinite m_t or m_H limit.

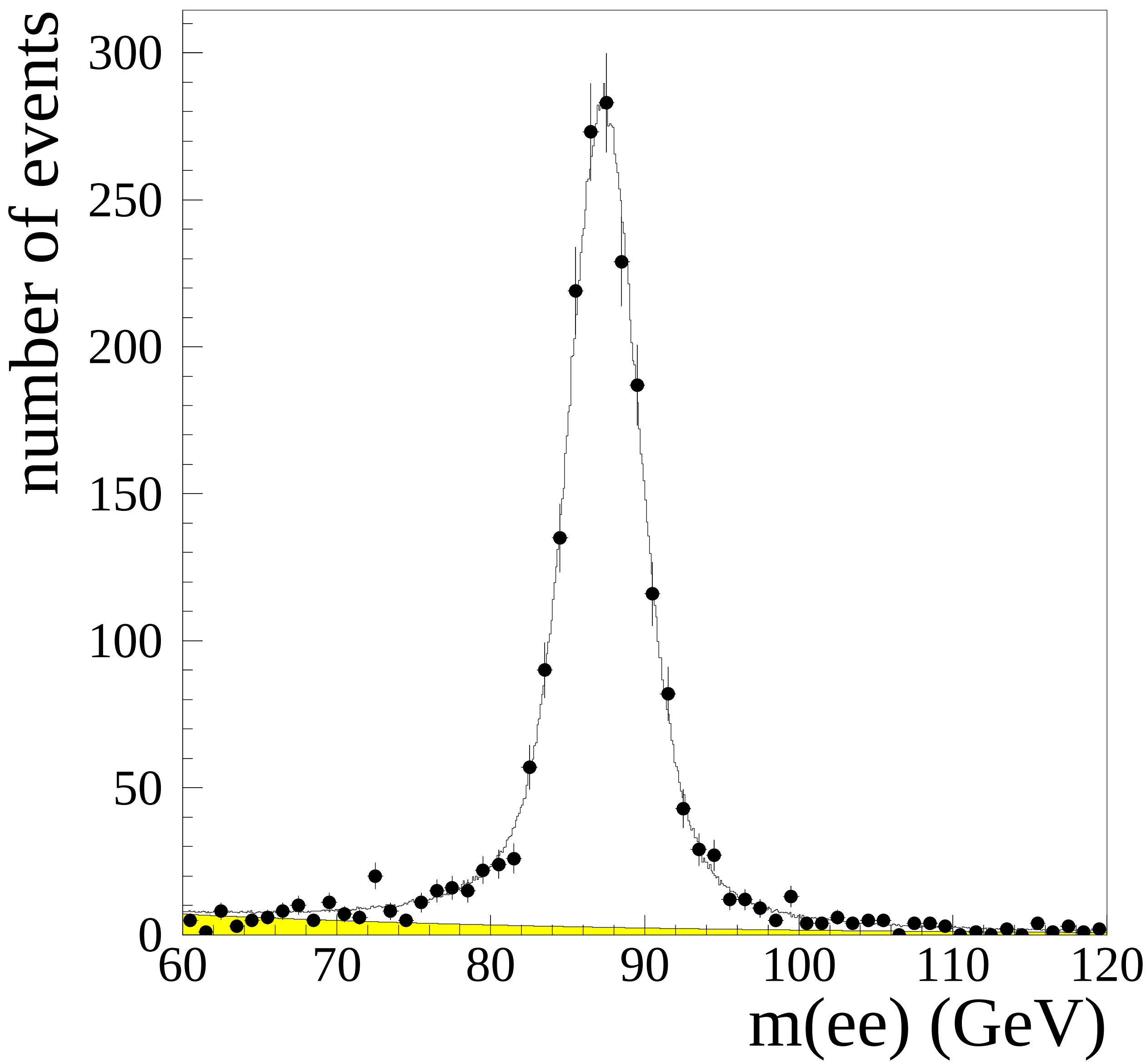
Thus a precise measurement of m_W and m_t not only tests the Standard Model but also constrains the Higgs mass.

I will discuss D0's W mass measurement using 1992-6 data, which is weeks from submission to PRD. A slightly less precise measurement by CDF exists as a preliminary result.

Method for *W* mass measurement

D0 compares the *W* mass to the precisely known *Z* mass, as measured in the same detector at the same time.

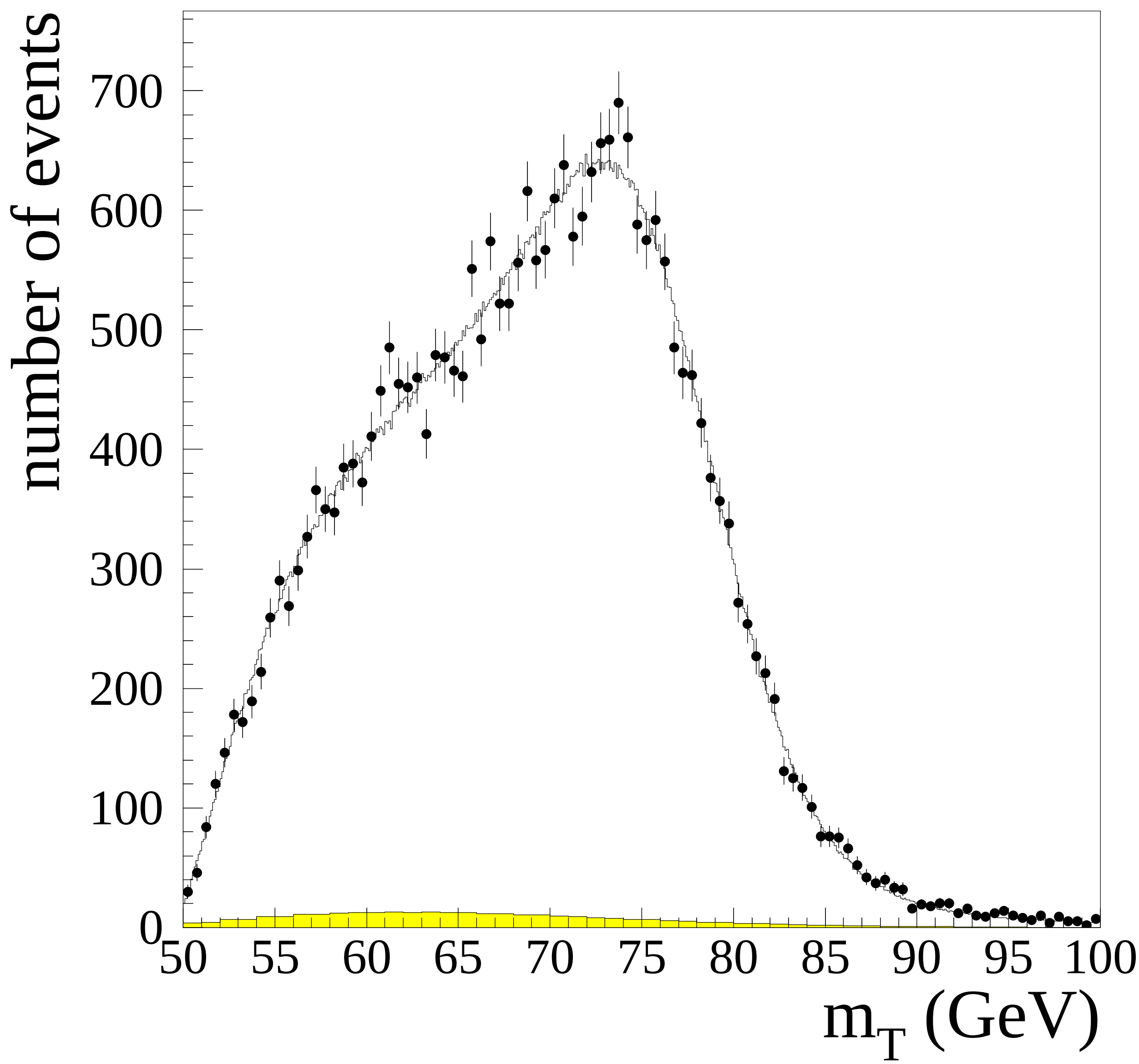
Plotted is the central-calorimeter *ee* mass spectrum from Run 1B data (points, 2179 events) and MC for *Z*+background (curve). The shaded region is the background.



Method for W mass measurement (cont'd)

Since the longitudinal component of the ν momentum cannot be deduced from transverse momentum balance, the W invariant mass can be calculated only in two dimensions.

This is the W transverse mass $m_T(W)$ plotted below (28 323 events from Run 1B). The D0 data show a Jacobian peak at the W mass.



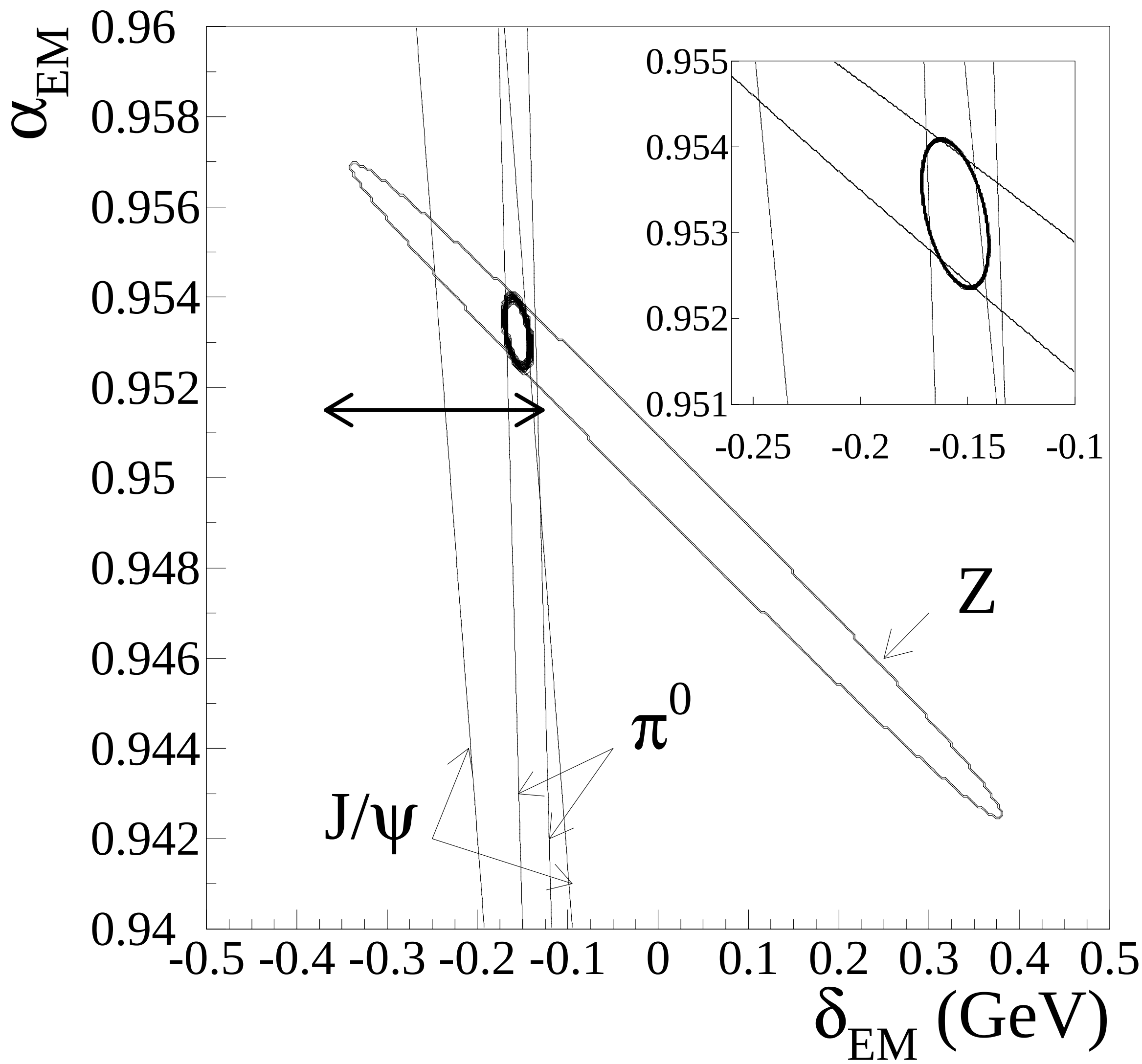
Electron energy calibration

The measured electron energy is related to the true energy by a constant slope factor α and an offset δ. The constraints on α and δ from the J/ψ (wide band), π^0 (narrow band), and Z data (large ellipse) combine to yield (small ellipse)

$$\alpha = 0.9533 \pm 0.0008$$

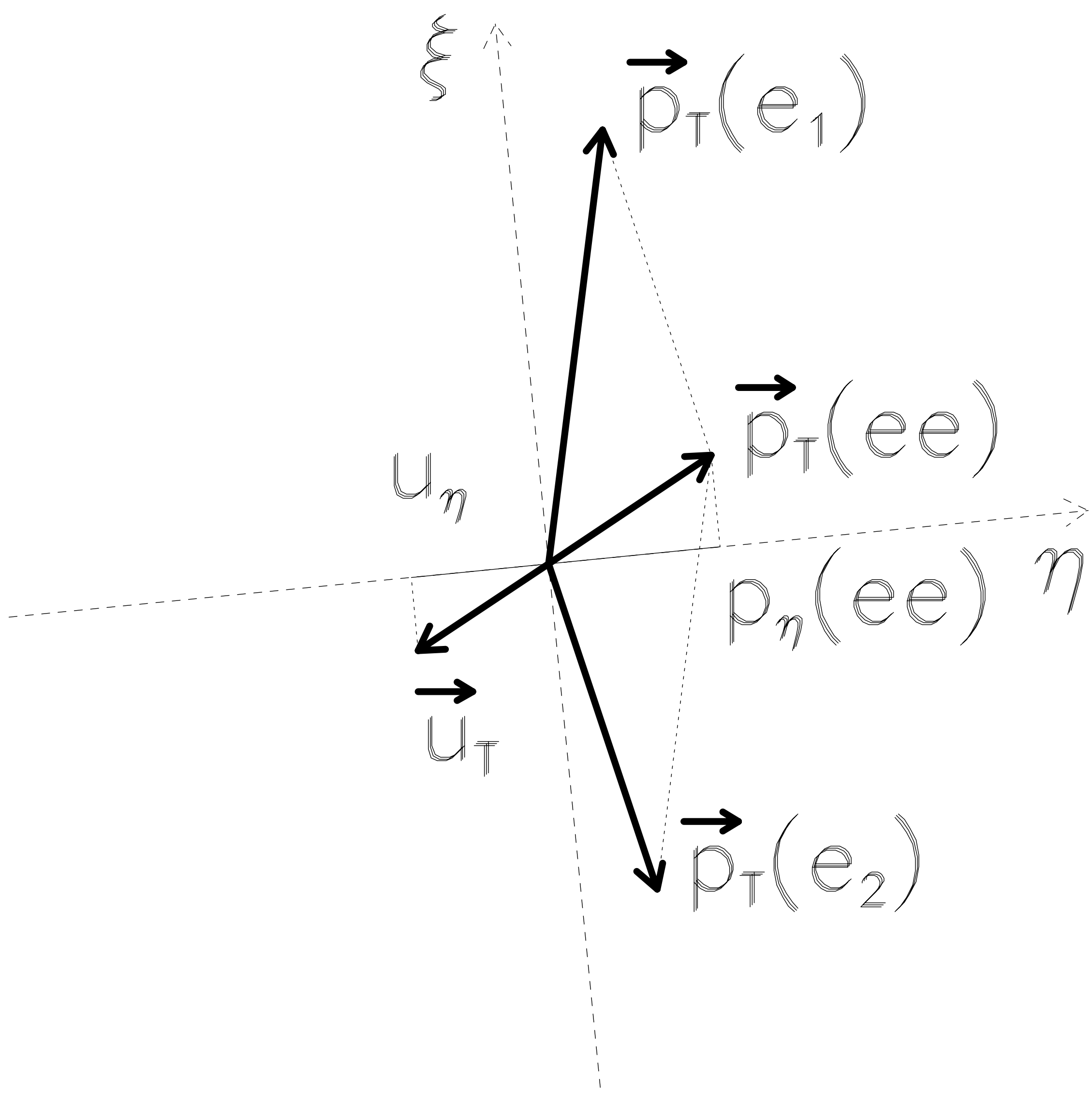
$$\delta = -0.16\,^{+0.03}_{-0.21}\ \text{GeV}\ .$$

$m(W)$ and $m(Z)$ are the same within 12%, so the error in δ propagates only weakly to the ratio $m(W)/m(Z)$. The resulting scale error on $m(W)$ from α and δ is 70 MeV.



Recoil momentum calibration

The response of the calorimeter to the (hadronic) recoil transverse momentum $\boldsymbol{u}_T$ is calibrated with *Z→ee* decays using the recoil component u_η along the bisector of the electron transverse momenta as shown.

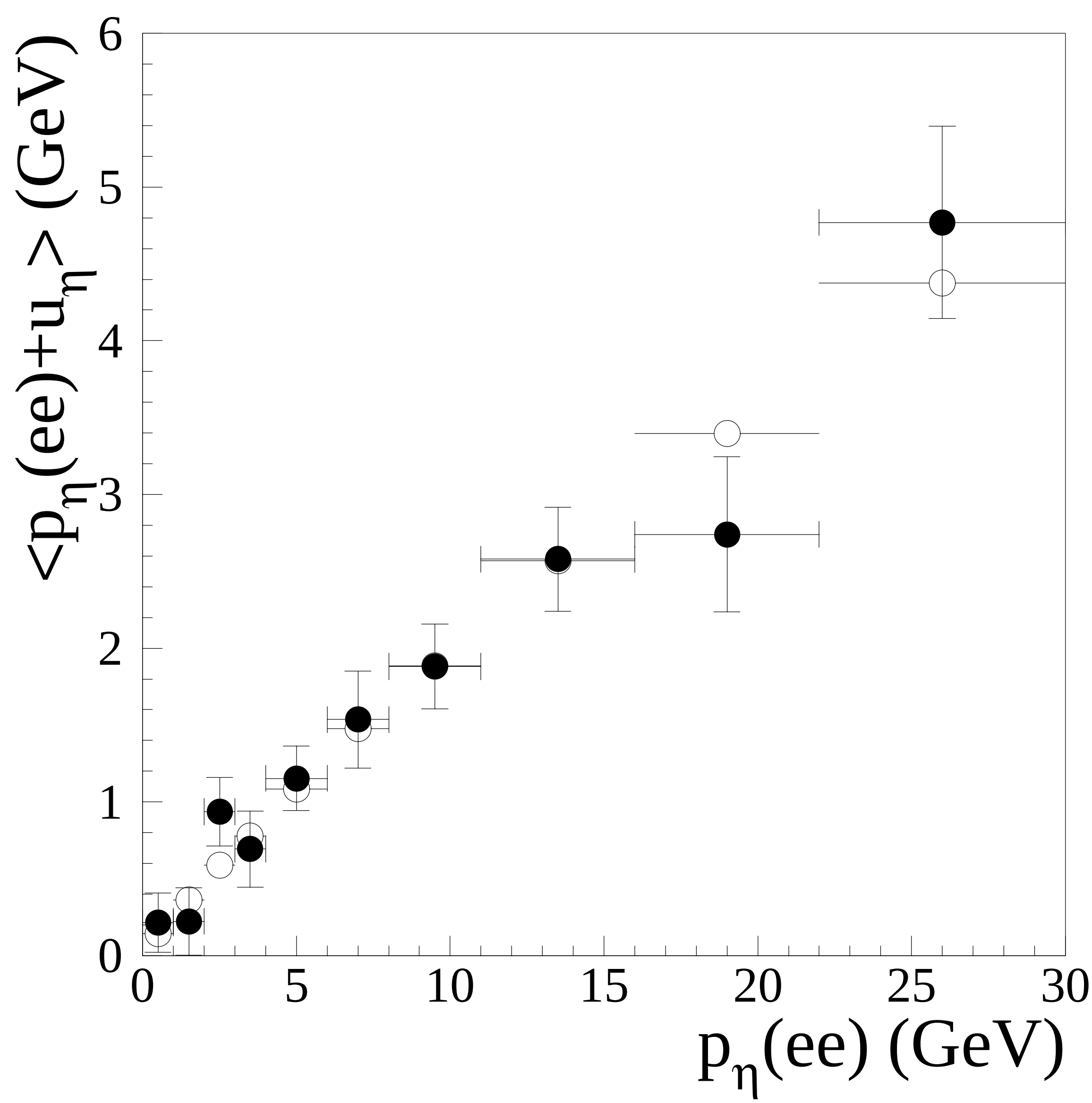


Recoil momentum calibration (cont'd)

The sum of the Z and raw recoil momenta along this bisector is plotted vs. the projected Z momentum only.

For a (hypothetical) perfect calorimeter the data points (solid) would all lie on the axis. Instead the hadronic recoil response is modeled (open points) by a function nearly constant at ~81% of the ideal value.

The systematic error in $m(W)$ due to hadronic energy scale is 20 MeV.

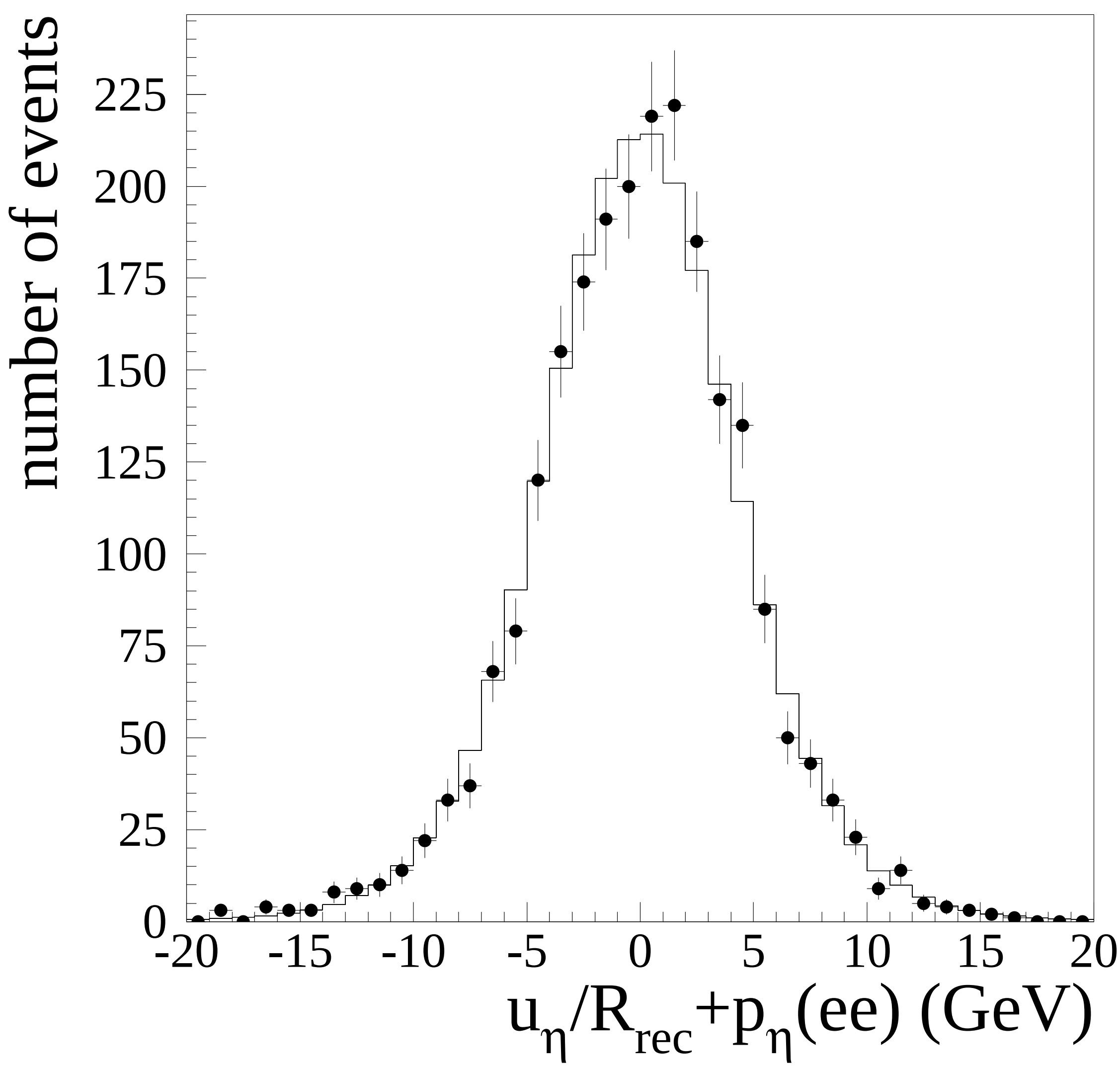


Recoil momentum resolution

The dispersion of these same data fixes the fractional energy resolution of the hard component of the hadronic recoil energy to be (0.49 ± 0.14)/√ $\boldsymbol{u}_T$. The points below are data and the histogram is MC.

The soft (azimuthally symmetric) component of the hadronic recoil momentum is modeled using the missing p_T from minimum bias events with the same mean number of interactions as the *W* sample.

The systematic error in $m(W)$ due to uncertainty in recoil momentum resolution is 25 MeV.

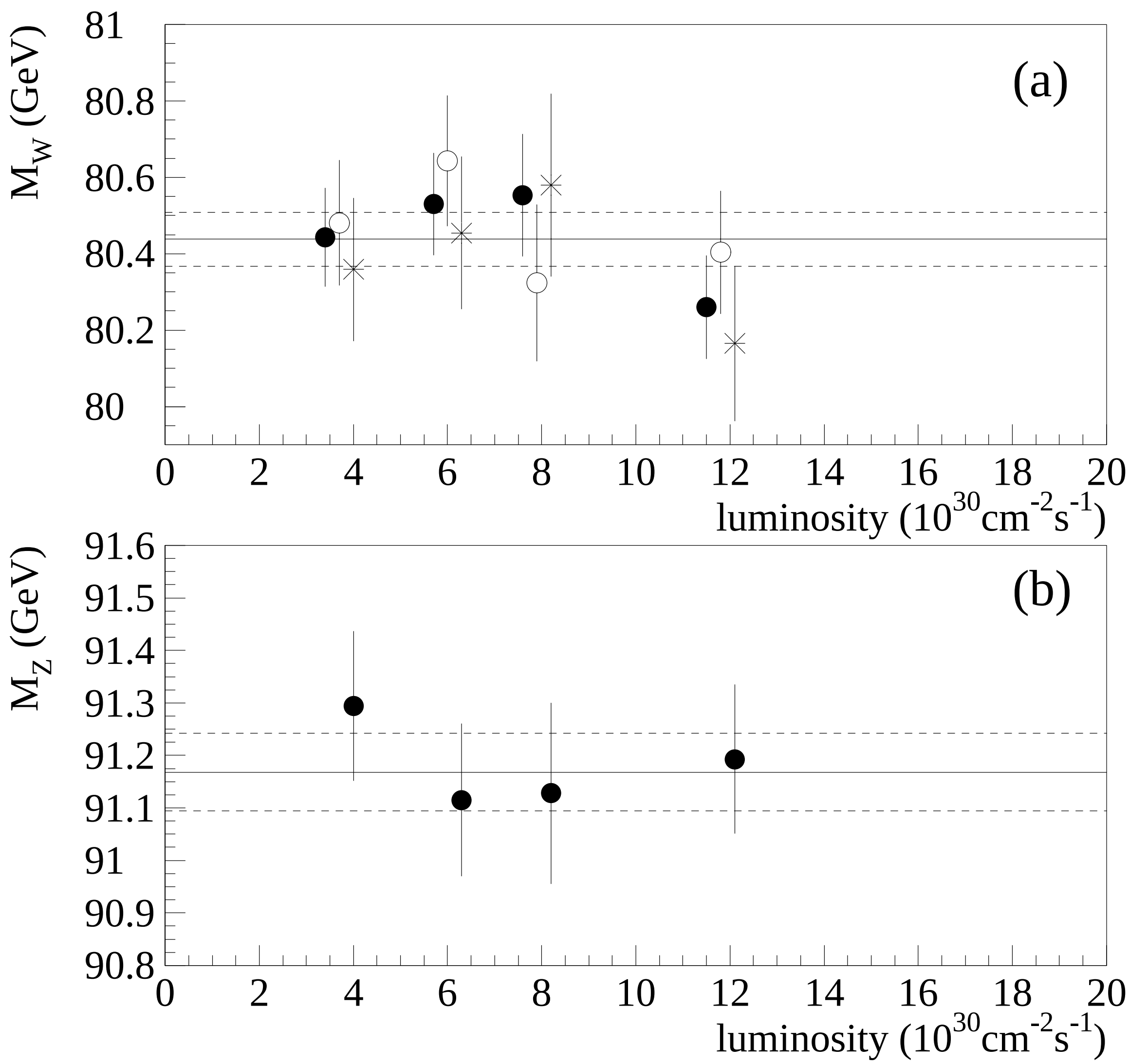


Luminosity dependence of fit to $m_T(W)$

The fit to the $m_T(W)$ distribution shown earlier yields a W mass of 80 438 ± 70(stat) MeV.

The χ^2 probability for this fit is 3%. The Kolmogorov-Smirnov probability is 38% within the fit window and 83% for the whole histogram.

When the data are divided into four luminosity regions, the fits to $m(W)$ and $m(Z)$ (below) are consistent with being independent of luminosity. In (a), solid points are from the fit to $m_T(W)$; open points from $p_T(e)$; * from $p_T(\nu)$.



W mass error summary and results

	1992/93	1995/96	common
M_W from m_T fit	80.35 GeV	80.44 GeV	
W statistics	140 MeV	70 MeV	
Z statistics	160 MeV	65 MeV	
calorimeter linearity			20 MeV
calorimeter uniformity			10 MeV
electron resolution	70 MeV	20 MeV	
electron angle calibration	40 MeV		30 MeV
recoil resolution	90 MeV	25 MeV	
recoil response	50 MeV	20 MeV	
electron removal	35 MeV	15 MeV	
selection bias	30 MeV	5 MeV	
backgrounds	35 MeV	10 MeV	
W production/decay			30 MeV
total uncertainty	255 MeV	105 MeV	50 MeV

The table summarizes the errors. Between the first and second D0 run, we were able to reduce them greatly.

Combining both runs, D0 obtains

$$M_W = 80.44 \pm 0.11 \text{ GeV.}$$

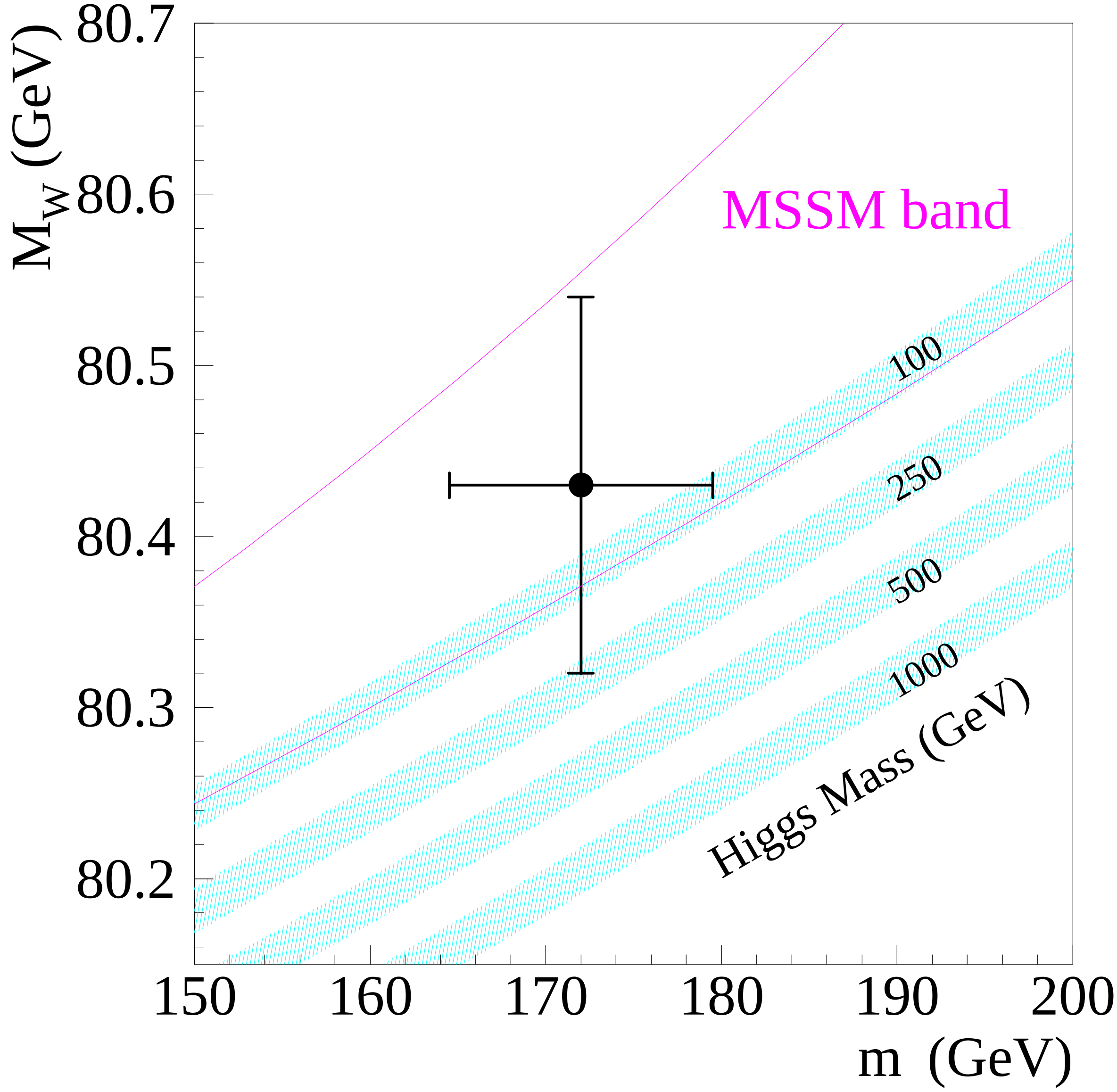
This result is close to being submitted for publication. It dominates the world average

$$M_W = 80.40 \pm 0.08 \text{ GeV.}$$

Context for *W* and top mass measurements

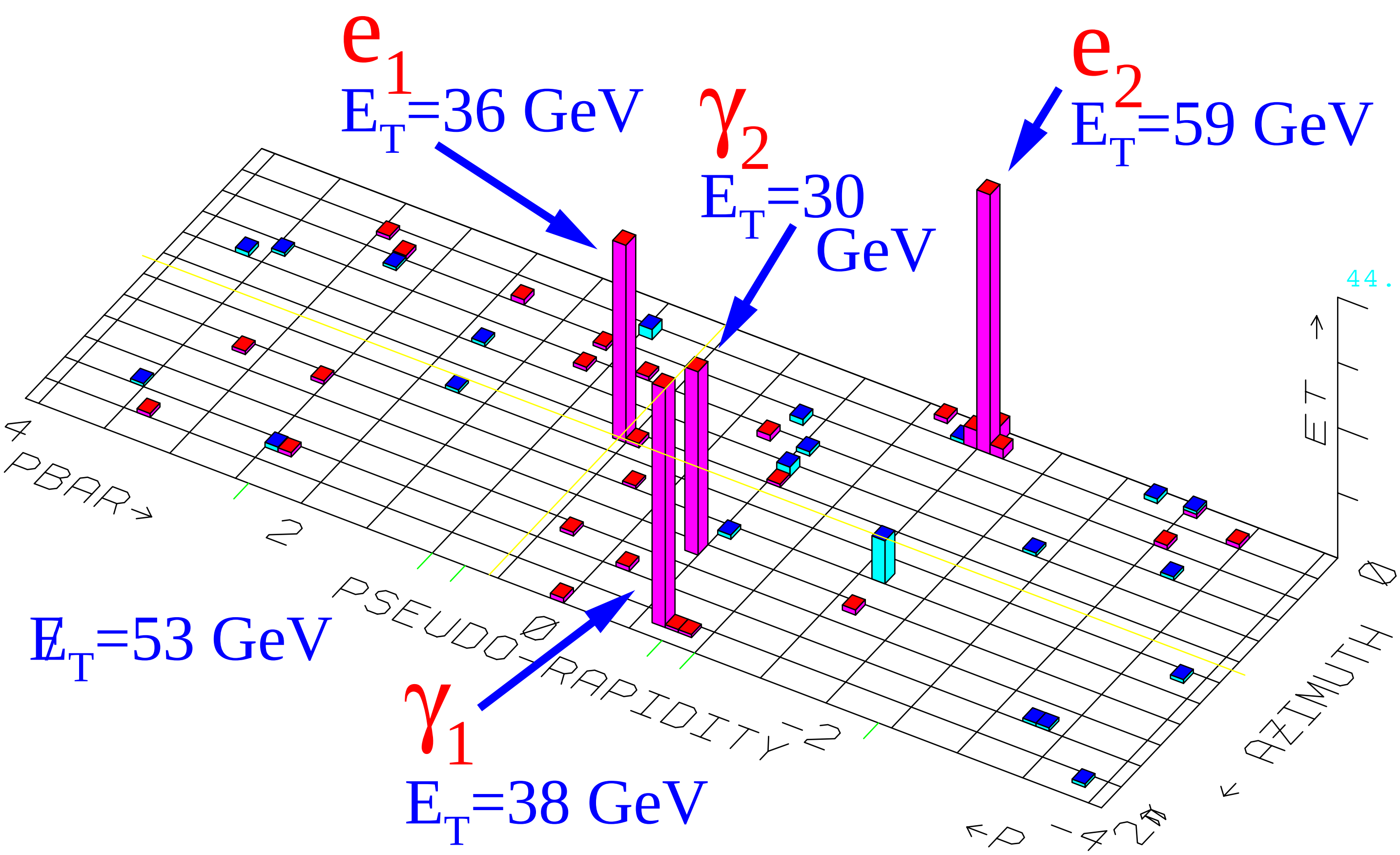
The D0 *W* and top mass measurements (solid point) are in agreement with CDF's preliminary measurement (added by hand).

Both the Tevatron points and other comparable Standard Model tests at LEP and SLD, in reasonable agreement, weakly favor a light Higgs boson in the general vicinity of the Minimal Supersymmetric Model prediction.



CDF *e`e’*γγ + missing E_T event

Much publicity has accompanied the CDF event shown below. It is a high E_T diphoton event with high missing E_T. The event includes two high E_T electron candidates as well, one of which is of good quality.



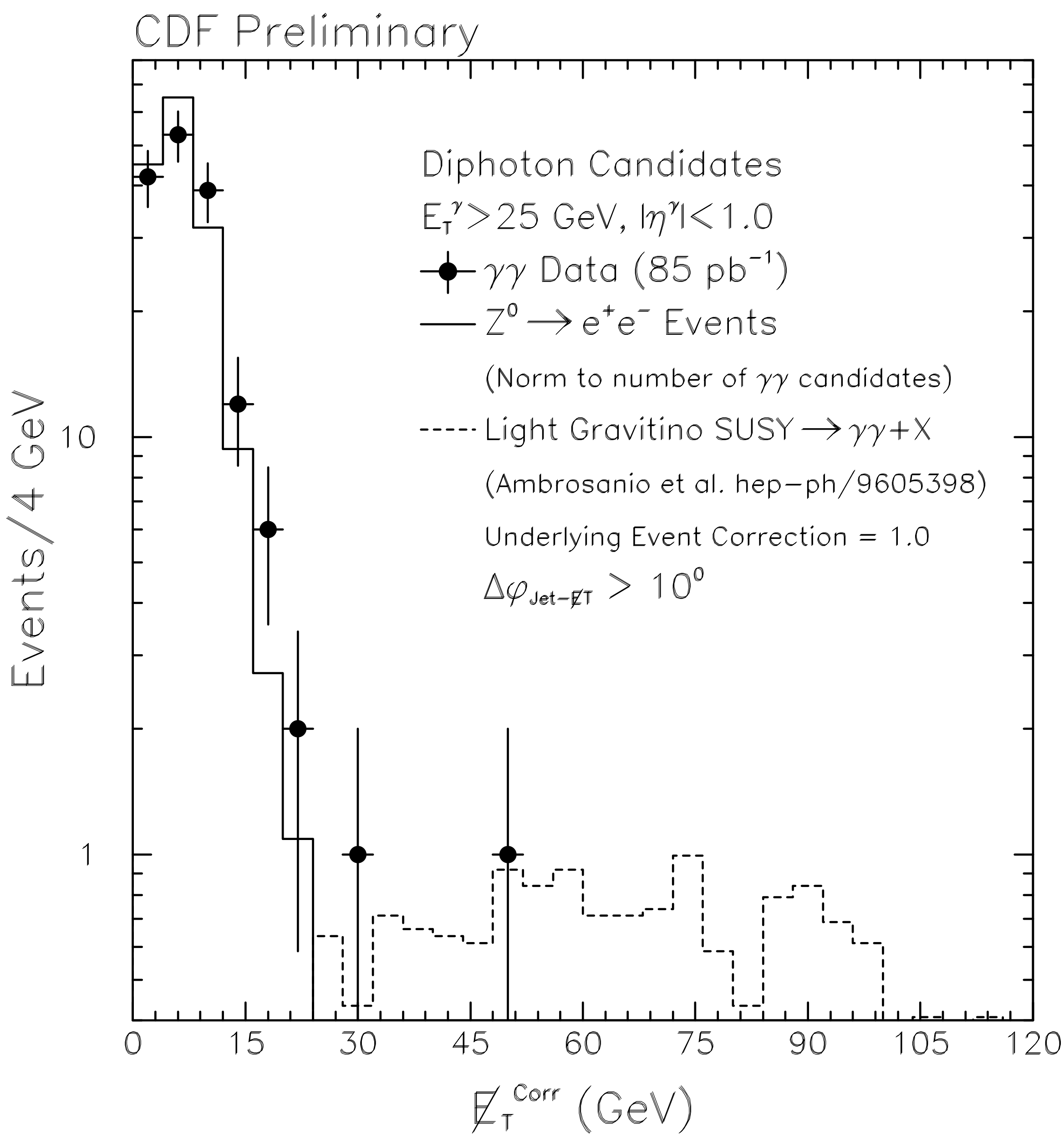
It is unusual because isolated leptons, photons, and especially missing E_T (indicating the presence of one or more ν’s) are rare compared to jets. Also there is little jet activity.

In principle it is very difficult to compute the probability that a particular event (with arbitrary, unexpected parameters) is background. How large a “box” in parameter space do we draw around the event? How many different topologies would we have regarded as equally rare?

$e^{`}e^{'}\gamma\gamma$ + missing E_T event (cont'd)

One approach to gauging the uniqueness of this event is to ignore a subset of its unusual characteristics and compare its remaining parameters to those of other events.

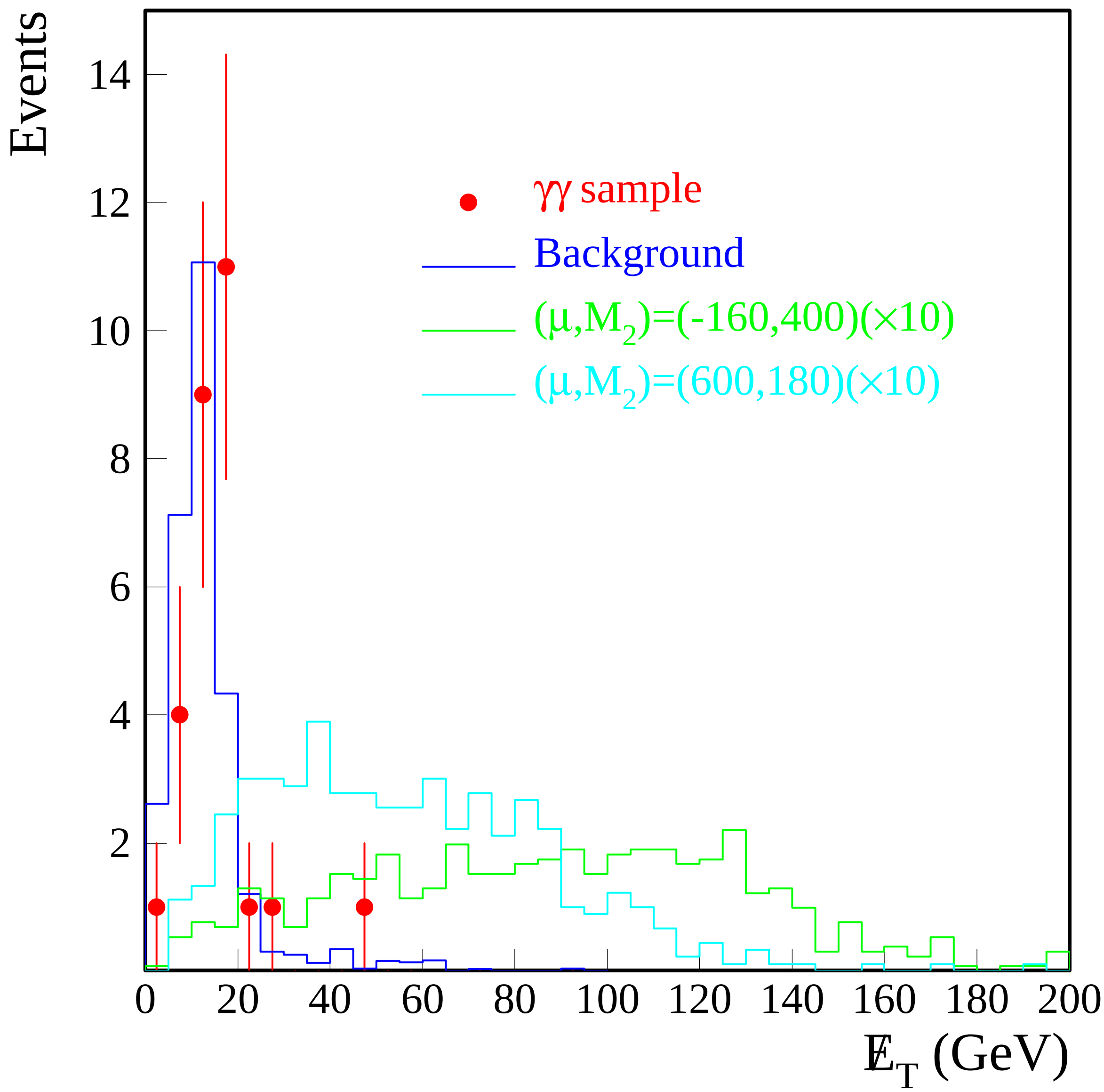
Here CDF ignores this event's electron candidates, plotting the missing E_T for all events that include two energetic photons. The $e^{`}e^{'}\gamma\gamma$ event has a missing E_T ~75% larger than that of its nearest competitor.



D0 missing E_T spectrum for diphoton events

A more sensitive study by D0 sets the E_T threshold for γ's at {20,12} rather than {25,25} GeV.

Again, the bulk of the missing E_T distribution is well below that of the *e*\`*e*'γγ event.



These diphoton missing E_T distributions illustrate the rarity of the *e*\`*e*'γγ event, independent of theoretical context.

They also rule out the existence of a companion sample of similar events, e.g. with <2 electrons detected.

SUSY context for the $e^+e^-\gamma\gamma$ + missing E_T event?

Arguments for SUSY in a nutshell:

In the Standard Model without the Higgs boson:

- fermions and gauge bosons are massless
- electroweak radiative corrections are infinite
- longitudinal W-W scattering grows boundlessly with energy

⇒ we need the Higgs.

In the Standard Model with the Higgs, but without SUSY:

- if radiative corrections to the Higgs mass are not to diverge;
- and if there is no new physics between the electroweak and Planck scales:
- then the Higgs potential must be tuned to one part in 10^{16} .

⇒ we think we need SUSY.

Other benefits of SUSY for grand unification:

- strong, EM, and weak coupling constants can converge at a scale around 10^{16} GeV, necessary for unification.
- the observed large top quark mass m_t can be accommodated naturally, provided that the Higgs mixing parameter tan β is in the range ~1-3.
- large m_t can explain why the quadratic part of the Higgs field is negative, yielding the "Mexican hat" potential that breaks electroweak symmetry.
- with the Yukawa coupling constants of the τ lepton and the b quark unified at the GUT scale, the observed top quark mass can be explained if tan β is either ~1 or ~35.

⇒ theorists have been relying on SUSY for many years -- but no direct experimental evidence for it exists.

SUSY context for the $e^- e^+ \gamma\gamma$ + missing E_T event? (cont'd)

After electroweak symmetry is broken, SUSY has two neutral Higgs bosons, h^0 and H^0, a charged Higgs H^+, and a pseudoscalar A^0. The h^0 mass is < ~130 GeV.

In SUSY the radiative corrections to the Higgs mass remain finite as a result of cancellations among diagrams involving the known particles and an undiscovered set of superpartners with couplings and charges the same, but with spins different by 1/2 unit.

Among the superpartners (e.g. squarks, gluinos, sleptons) the gauginos play a key role in SUSY searches. There are two charged superpartners $\chi^+_{1,2}$ of the charged gauge bosons W^+ and H^+, and four neutral gauginos $\chi^0_{1,2,3,4}$, superpartners of the neutral gauge bosons γ, Z, h, and H.

To avoid artificial tuning of parameters to satisfy known limits on lepton and baryon violating interactions, R parity, a conserved multiplicative quantum number, is introduced. Known particles have R=+1, but superpartners have R=–1.

Conservation of R parity implies that the the lightest supersymmetric particle, or LSP, is stable. In any interaction of known particles that produces supersymmetry, at least two LSP's escape undetected.

In most SUSY models, the lightest neutral gaugino χ^0_1 is the LSP. However, in gauge mediated models, the gravitino, superpartner of the graviton, is the LSP.

SUSY context for the e`e'$\gamma\gamma$ + missing E_T event? (cont'd)

Now for the SUSY interpretations of CDF's e`e'$\gamma\gamma$ event.

If the LSP is the $\chi^0{}_1$, a possible SUSY interpretation begins with production of a pair of selectrons. Each decays to an electron plus $\chi^0{}_2$. In one region of parameter space the $\chi^0{}_2$ decays with high probability to $\chi^0{}_1 + \gamma$. This accounts for the e's, the γ's, and the missing E_T (from the LSP's).

There is a similar scenario involving initial production of a pair of charged gauginos, or a chargino and a neutralino.

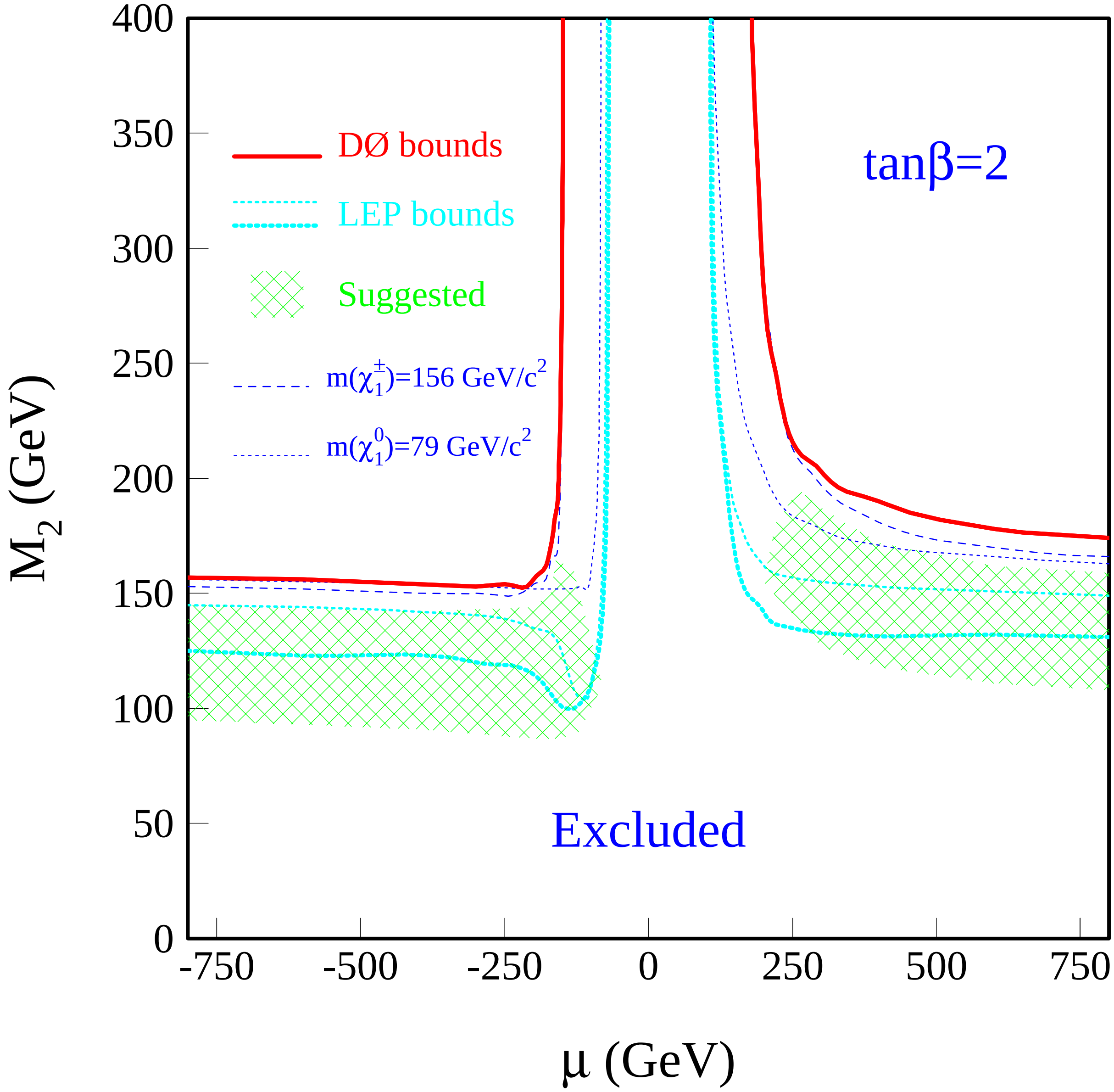
If the LSP is the gravitino, the SUSY interpretation is perhaps more natural. The scenario is similar to the above, except that the intermediate $\chi^0{}_2$ is no longer needed to generate the photons. Instead, assuming that the coupling between the gravitino and matter is large enough, the $\chi^0{}_1$ decays to gravitino + photon within the detector.

In fact, with this assumption, any pair production of supersymmetric partners results in two photons plus missing E_T (from two gravitinos). This is a strong motivation for the CDF and D0 searches just described.

D0 limits on charged-neutral gaugino pair production in light gravitino SUSY

Fixing the ratio of MSSM parameters M_1 and M_2 , D0 assumes that sleptons and selectrons are too heavy to play a role in the gaugino cascade, and $\chi_1^0 \rightarrow \gamma G$ with BR=1.

D0 excludes (e.g. for tan $\beta = 2$) a large portion of the $\mu - M_2$ plane, including the full (hatched) region proposed to account for CDF's $e`e'\gamma\gamma$ event.



Prognosis: CDF and D0

Run 2 of the Fermilab Tevatron is now planned to begin in Spring 2000, after the Main Ring is replaced by the Main Injector. Its faster repetition rate will ~triple the antiproton production rate, and its larger phase space acceptance will benefit both the proton and antiproton beams. A factor ~5 increase in luminosity is expected.

A further factor of ~2-3 is sought from “recycling” the antiprotons from the collider, recooling them with electrons, and storing them in a new small ring made from permanent magnets.

Both CDF and D0 are being upgraded to match these new capabilities. These upgrades have two aspects:

- Improving detector resolving time, data acquisition rate, and trigger selectivity in order to survive these high rates.
- Adding qualitatively new capability.

Particularly worthy of note in the latter category are the addition to D0 of a central solenoidal 2T magnetic field (for momentum analysis of charged particles) and a silicon vertex detector, like CDF’s, for identification of displaced vertices e.g. from *b* quarks.

Carrying out these upgrades, to the accelerator as well as detectors, will be as challenging as was their original construction.

Prognosis: top and W physics, and SUSY searches

For constraining the Higgs mass, the present top quark mass error is more than adequate compared to the W mass error. A factor of two improvement in Run 2 would be useful at that point and is within reach.

From LEP II in the next few years, a factor of two reduction in the world average W mass error is expected. In Run 2, Fermilab will have the opportunity to confirm and perhaps extend these new LEP measurements.

I have described only one facet of a broad search for SUSY in which LEP as well as Fermilab is heavily engaged. Their searches are competitive but also complementary in many instances.

LEP II is sensitive to a light Higgs mass up to ~80 GeV, extending to ~100 GeV in the next few years. Some years after that, Fermilab should be able to further expand the window of sensitivity to the Higgs, while continuing its vigorous searches for other SUSY hints.

In ~2006, at 7 times Fermilab's C.M. energy, LHC expects with some confidence to be able to map out the general features of the SUSY states, if in fact they exist -- and to find the Higgs particle(s), even if they aren't light.